B physics beyond CKM

Zoltan Ligeti

Warning: ♻ APS/JPS meeting Nov.2; ♻ BaBar workshop Dec.7

- Introduction
  The flavor problems
- Mixing in the B_d and B_s systems
  Implications of the measurement of Δm_s
  Bounds on non-SM contributions
- Some topics with interesting progress
  CP violation ($b \to s$ penguins, angles α and γ)
  Inclusive decays ($|V_{xb}|$, rare decays)
  Exclusive processes (2-body nonleptonic decays)
- Conclusions

Why is flavor physics and CPV interesting?

- SM flavor problem: hierarchy of masses and mixing angles
- NP flavor problem: TeV scale (hierarchy problem) $\ll$ flavor & CPV scale

  ϵ_K: $\dfrac{(s\bar{d})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^4\,\mathrm{TeV}$, $\quad B_d$ mixing: $\dfrac{(b\bar{d})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^3\,\mathrm{TeV}$

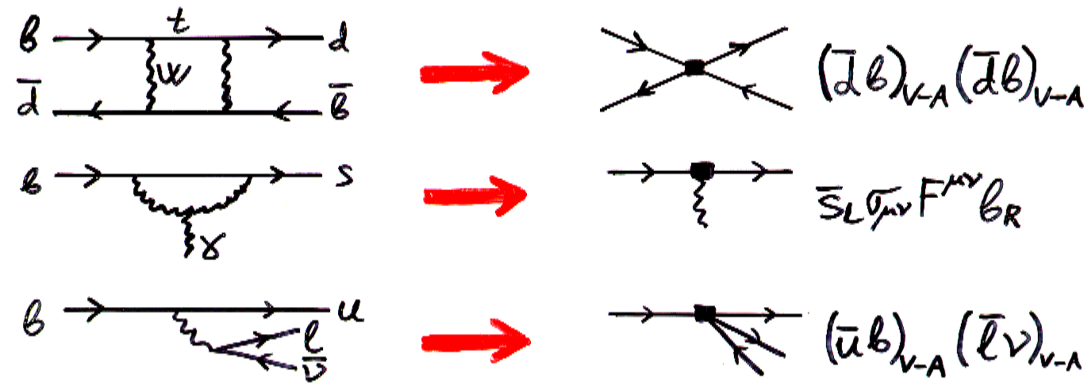
- Almost all extensions of the SM have new sources of CPV & flavor conversion
  (e.g., 43 new CPV phases in SUSY)
- A major constraint for model building
  (flavor structure: universality, heavy squarks, squark-quark alignment, ...)
- The observed baryon asymmetry of the Universe requires CPV beyond the SM
  (not necessarily in flavor changing processes, nor in the quark sector)

What are we after?

- At scale m_b, flavor changing processes are mediated by $\mathcal{O}(100)$ higher dimension operators

  Depend only on a few parameters in the SM $\Rightarrow$ correlations between s, c, b, t decays

weak / NP scale $\qquad\qquad \sim 5$ GeV



E.g.: in SM $\dfrac{\Delta m_d}{\Delta m_s}, \dfrac{b \to d\gamma}{b \to s\gamma}, \dfrac{b \to d\ell^+\ell^-}{b \to s\ell^+\ell^-} \propto \left|\dfrac{V_{td}}{V_{ts}}\right|$, but test different short dist. physics

- Does the SM (i.e., integrating out virtual W, Z, and quarks in tree and loop diagrams) explain all flavor changing interactions? Right coefficients and operators?

  Study SM loops (mixing, rare decays), interference (CPV), tree vs. loop processes

Spectacular track record

- Flavor and CP violation have been excellent probes of “new physics”
  - Absence of $K_L \to \mu\mu$ predicted charm
  - ϵ_K predicted 3rd generation
  - Δm_K predicted charm mass
  - Δm_B predicted heavy top
- If there is NP at the TEV scale, it must have a very special flavor / CP structure
- Or will the LHC find just a SM-like Higgs?

SM tests with K and D mesons

- CPV in K system is at the right level (ϵ_K accommodated with $\mathcal{O}(1)$ CKM phase)
- Hadronic uncertainties preclude precision tests (ϵ'_K notoriously hard to calculate)
- $K \to \pi\nu\bar{\nu}$: Theoretically clean, but rates small $\mathcal{B} \sim 10^{-10}(K^\pm)$, $10^{-11}(K_L)$

  Observation (3 events): $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.5^{+1.3}_{-0.9}) \times 10^{-10}$ — need more data

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- D system: complementary to K and B

  Only meson where mixing is generated by down type quarks (SUSY: up squarks)

  CPV, FCNC both GIM and CKM suppressed $\Rightarrow$ tiny in SM and not yet observed

  $$y_{CP} = \frac{\Gamma(CP\text{ even}) - \Gamma(CP\text{ odd})}{\Gamma(CP\text{ even}) + \Gamma(CP\text{ odd})} = (0.9 \pm 0.4)\%$$

  No mixing also disfavored by $> 2\sigma$ in 2-d fit to $(\Delta m, \Delta\Gamma)$ at Babar & Belle

- At the present sensitivity, CPV would be the only clean signal of NP in D mixing

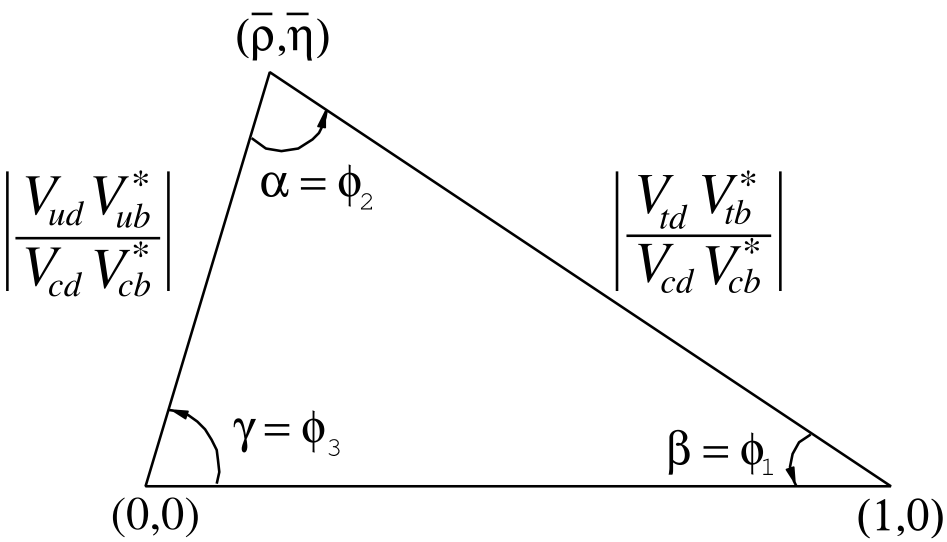
  Could also discover NP via FCNC, e.g., $D \to \pi\ell^+\ell^-$

CKM matrix and unitarity triangle

- Exhibit hierarchical structure of CKM $(\lambda \simeq 0.23)$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\bar\rho - i\bar\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- Measurements often shown in $(\bar\rho, \bar\eta)$ plane — a "language" to compare data

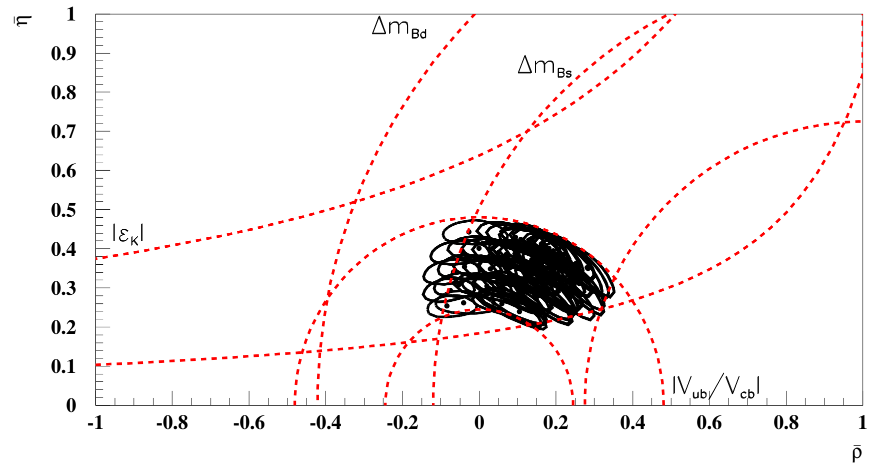


$$V_{ud}\,V_{ub}^* + V_{cd}\,V_{cb}^* + V_{td}\,V_{tb}^* = 0$$

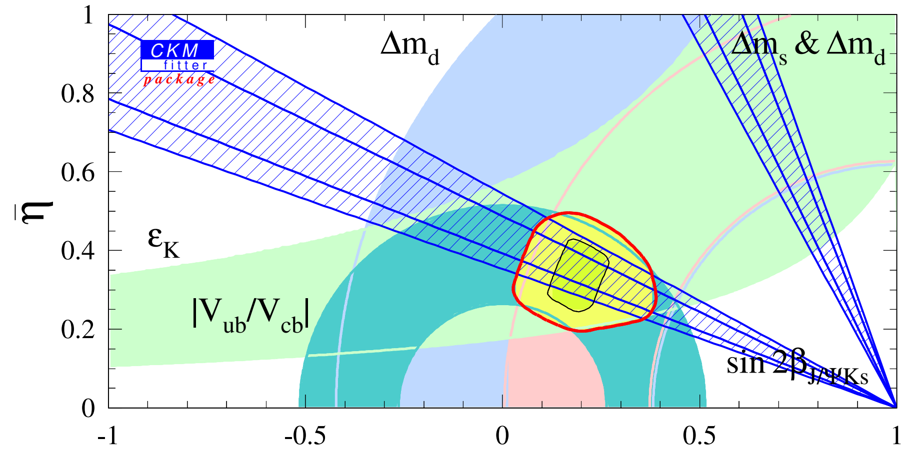
Angles and sides are directly measurable in numerous different processes

Goal: overconstraining measurements sensitive to different short dist. phys.

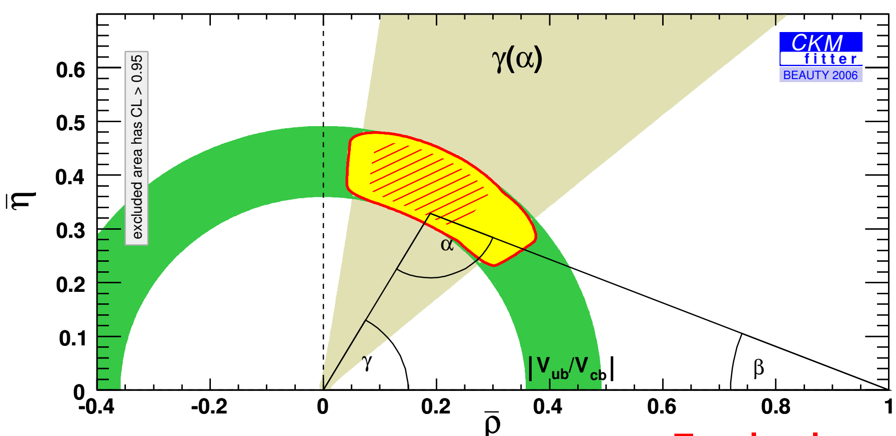
Remarkable progress at B factories



(1998)

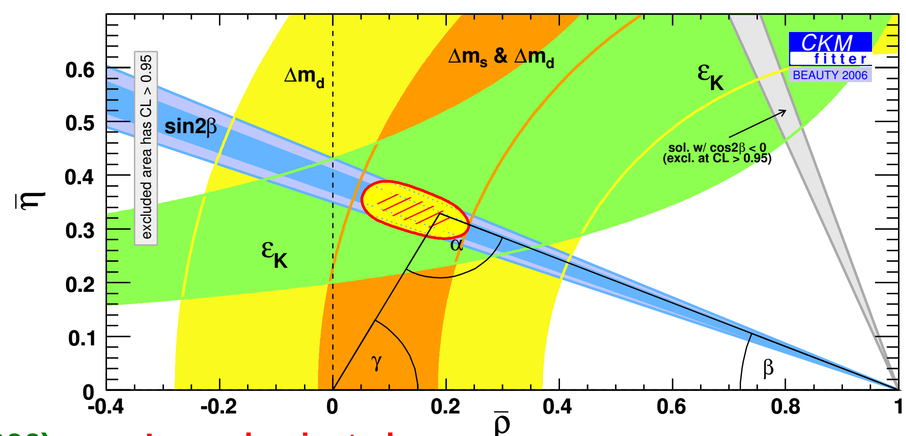


(2002) **K vs. B constraints**



Tree-level

(2006)



Loop-dominated

- The CKM picture is verified $\Rightarrow$ looking for corrections rather than alternatives

The B factory era

PDG particle data group $\Rightarrow$ BDG particle data group

The B factory era

- Q: How many CP violating quantities are measured with $> 3\sigma$ significance?

  A: 6? 9? 12? 15? (with different sensitivity to NP)

The B factory era

- Q: How many CP violating quantities are measured with $> 3\sigma$ significance?

  A: 12 (with different sensitivity to NP)

  ϵ_K, ϵ'_K,

  $S_{\psi K}$, $S_{\eta' K}$, $S_{K^+K^-K^0}$, $S_{D^{*+}D^{*-}}$, $S_{\pi^+\pi^-}$,

  $A_{K^-\pi^+}$, $A_{\eta K^{*0}}$, $A_{\pi^+\pi^-}$, $A_{\rho\pi}^{-+}$, $a_{D^{*\pm}\pi^\mp}$

- Just because a measurement determines a CP violating quantity, it no longer automatically implies that it is interesting

  (If $S_{\eta' K}$ was still consistent with 0, it would be a clear discovery of new physics!)

- It does not matter whether one measures a side or an angle — only experimental precision and theoretical cleanliness for interpretation for short distance physics

Mixing in the $B_{d,s}$ systems

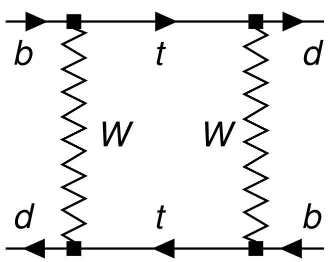
$B\overline{B}$ mixing: matter – antimatter oscillation

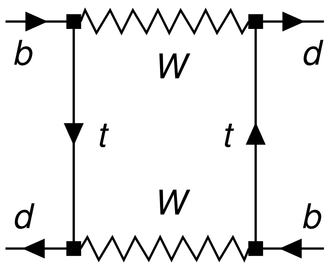
- Two flavor eigenstates: $|B^0\rangle = |\bar{b}\, d\rangle, \quad |\overline{B}^0\rangle = |b\, \bar{d}\rangle$

  Time evolution: $$i\,\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}|B^0(t)\rangle\\|\overline{B}^0(t)\rangle\end{pmatrix} = \left(M - \frac{i}{2}\,\Gamma\right)\begin{pmatrix}|B^0(t)\rangle\\|\overline{B}^0(t)\rangle\end{pmatrix}$$

  M, Γ are 2×2 Hermitian matrices; $CPT \Rightarrow M_{11} = M_{22}$, $\Gamma_{11} = \Gamma_{22}$

- M_{12} dominated by box diagrams with top (GIM $+$ CKM hierarchy) — sensitivity to high scales





  Mass eigenstates: $|B_{H,L}\rangle = p|B^0\rangle \mp q|\overline{B}^0\rangle$

  Time dependence: $|B_{H,L}(t)\rangle = e^{-(iM_{H,L}+\Gamma_{H,L}/2)t}|B_{H,L}\rangle$ involve mixing and decay

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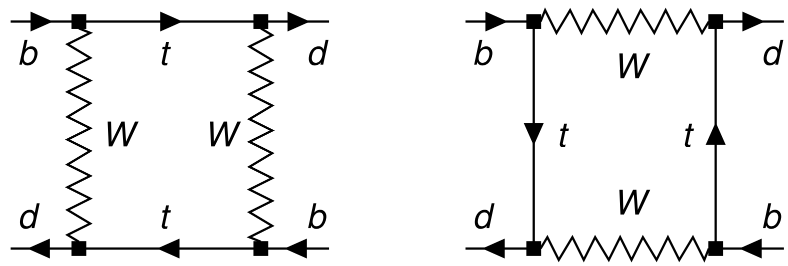

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- In $|\Gamma_{12}| \ll |M_{12}|$ limit, which holds for both $B_{d,s}$ within and beyond the SM

  $$\Delta m = 2|M_{12}|\,, \quad \Delta\Gamma = 2|\Gamma_{12}|\cos\phi_{12}\,, \quad \phi_{12} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$ $\Rightarrow$ NP cannot enhance $\Delta\Gamma_s$

Parameterize new physics in mixing

- Assume: (i) 3×3 CKM matrix is unitary; (ii) Tree-level decays dominated by SM

  Concentrate on NP in mixing amplitude; two parameters for each neutral meson:

$$M_{12} = \underbrace{M_{12}^{\rm SM}\, r^2\, e^{2i\theta}}_{\text{easy to relate to data}} \equiv \underbrace{M_{12}^{\rm SM}(1 + h\, e^{2i\sigma})}_{\text{easy to relate to models}}$$

- Tree-level CKM constraints unaffected: $|V_{ub}/V_{cb}|$ and γ (or $\pi - \beta - \alpha$)

- $B\overline{B}$ mixing dependent observables sensitive to NP: $\Delta m_{d,s}$, S_{f_i}, $A_{\rm SL}^{d,s}$, $\Delta\Gamma_s$

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$$\Delta m_{B_q} = r_q^2\, \Delta m_{B_q}^{\rm SM} = |1 + h_q e^{2i\sigma_q}|\Delta m_q^{\rm SM}$$

$$S_{\psi K} = \sin(2\beta + 2\theta_d) = \sin[2\beta + \arg(1 + h_d e^{2i\sigma_d})] \qquad S_{\rho\rho} = \sin(2\alpha - 2\theta_d)$$

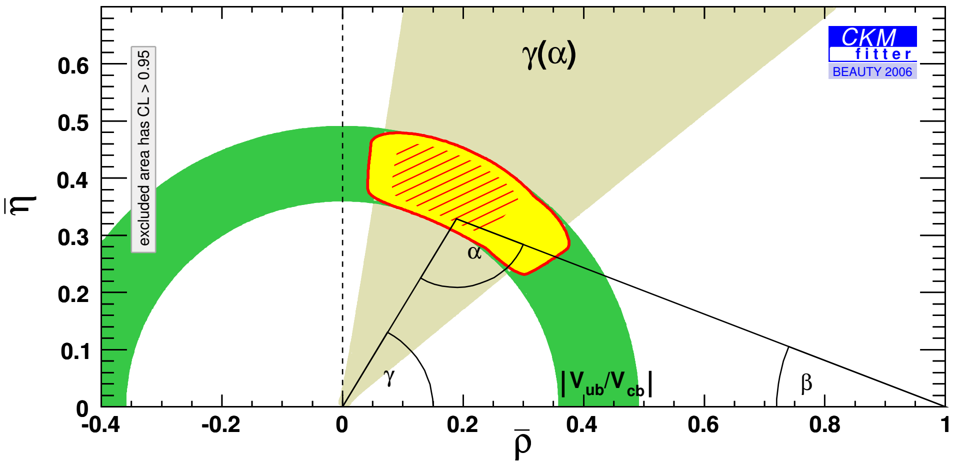
$$S_{\psi\phi} = \sin(2\beta_s - 2\theta_s) = \sin[2\beta_s - \arg(1 + h_s e^{2i\sigma_s})]$$

$$A_{\rm SL}^q = {\rm Im}\left(\frac{\Gamma_{12}^q}{M_{12}^q r_q^2\, e^{2i\theta_q}}\right) = {\rm Im}\left[\frac{\Gamma_{12}^q}{M_{12}^q(1 + h_q e^{2i\sigma_q})}\right] \qquad \Delta\Gamma_s = \Delta\Gamma_s^{\rm SM} \cos^2 2\theta_s$$

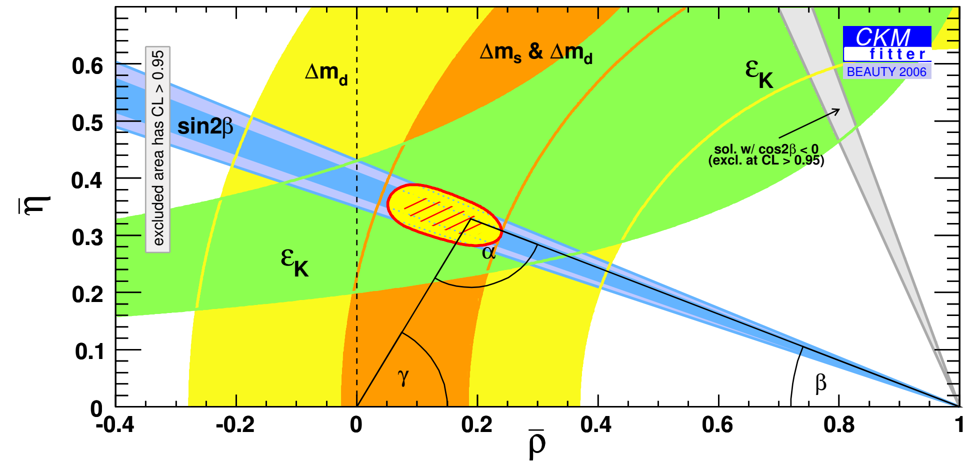
Constraining new physics in loops

- B factories determined $\bar\rho, \bar\eta$ from (effectively) tree-level & loop-induced processes

Tree-dominated



Loop-induced



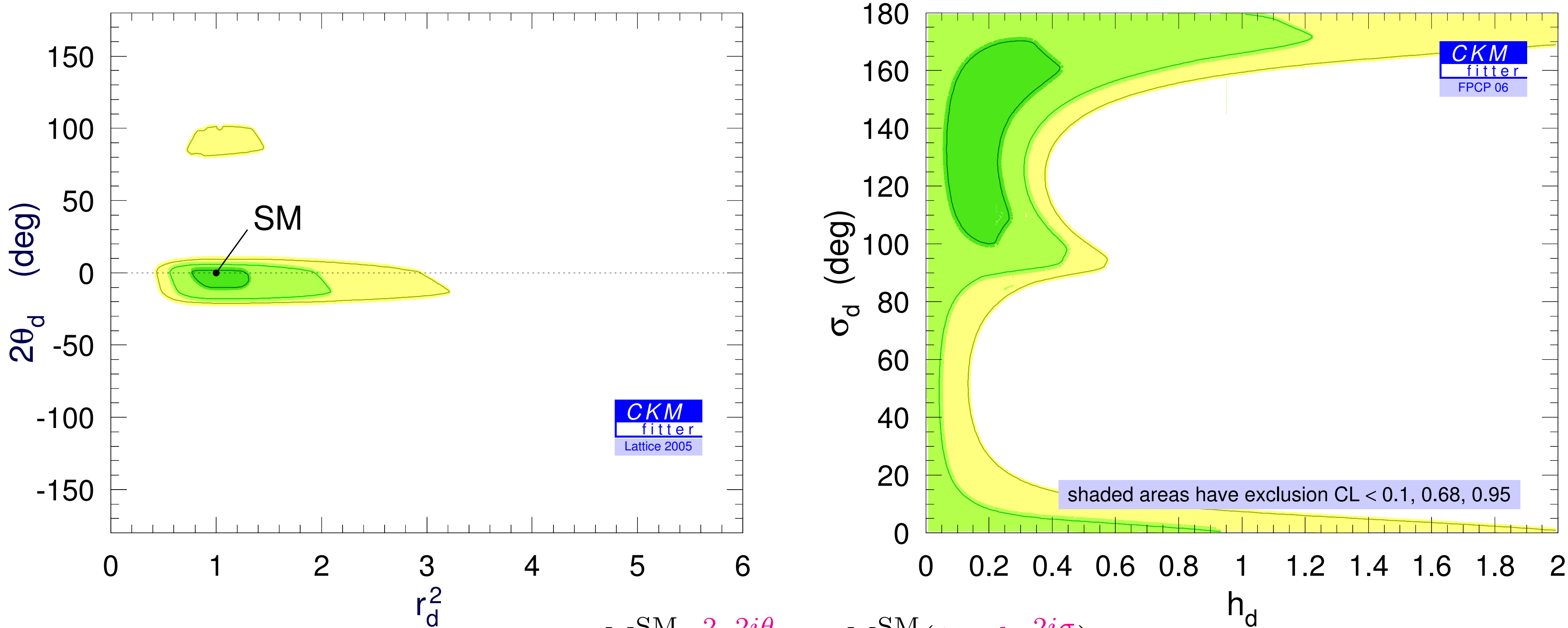
- Even in the presence of NP in loops, $\bar\rho, \bar\eta$ constrained to SM region (caveat: α)

  (Was completely unconstrained before B factories turned on!)

- ϵ_K, Δm_d, Δm_s, etc., can be used to overconstrain the SM and test for NP

  Beyond SM: more parameters $\Rightarrow$ independent measurements critical

NP parameters r_d^2, θ_d and h_d, σ_d



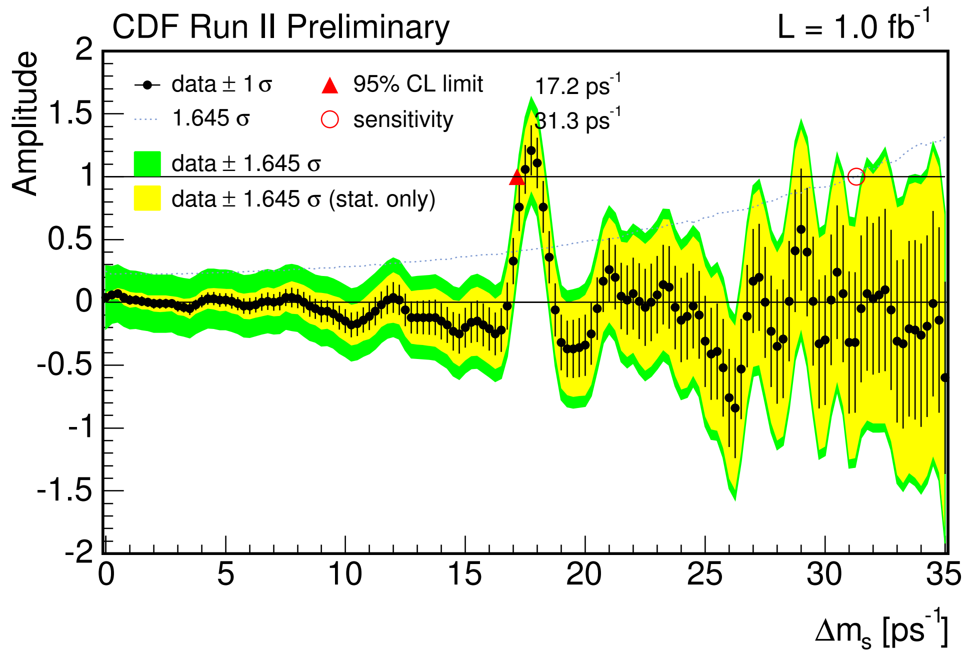
$$M_{12}^{\rm SM}\, r^2 e^{2i\theta} \;\equiv\; M_{12}^{\rm SM}(1 + h e^{2i\sigma})$$

- $h_d\,, \sigma_d$: NP may still be comparable to SM: $h_d = 0.23\,^{+0.57}_{-0.23}$, i.e., $h_d < 1.7$ (95% CL)
- Sizable non-SM contributions to most loop-mediated transitions are still allowed

The news of 2006: Δm_s

- $\Delta m_s = (17.77 \pm 0.10 \pm 0.07)\,\mathrm{ps}^{-1}$

  A 5.4σ measurement [CDF, hep-ex/0609040]



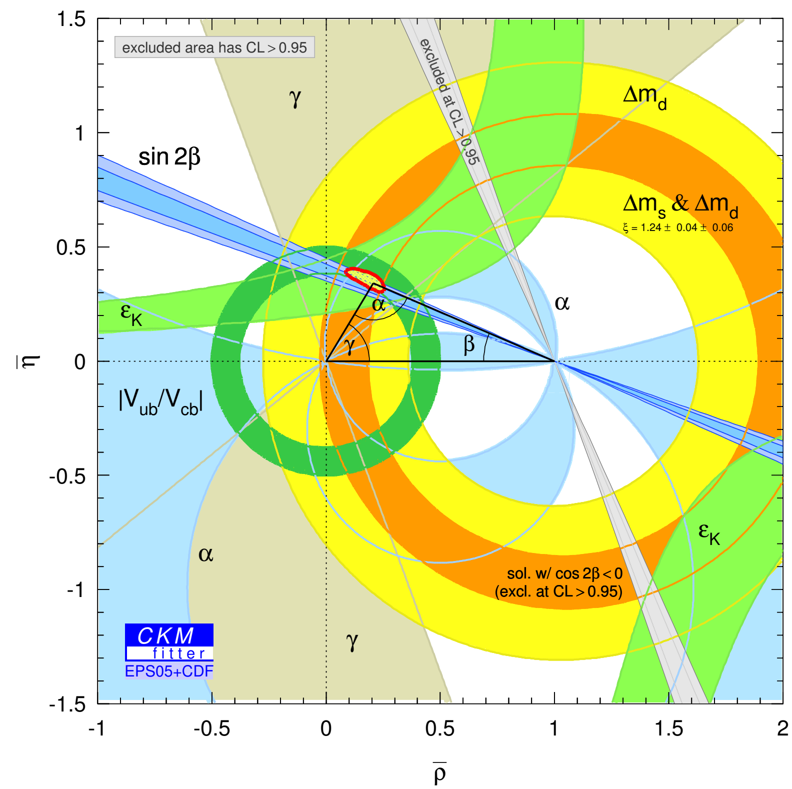
Uncertainty $\sigma(\Delta m_s) = 0.7\%$ is already smaller than $\sigma(\Delta m_d) = 0.8\%$!

- Largest uncertainty: $\xi = \dfrac{f_{B_s}\sqrt{B_s}}{f_{B_d}\sqrt{B_d}}$

  Chiral logs: $\xi \sim 1.2$ [Grinstein et al., '92]

  SM CKM fit: $\xi = 1.158^{+0.096}_{-0.064}$

  Using $\xi_{\mathrm{LQCD}} = 1.24 \pm 0.04 \pm 0.06$



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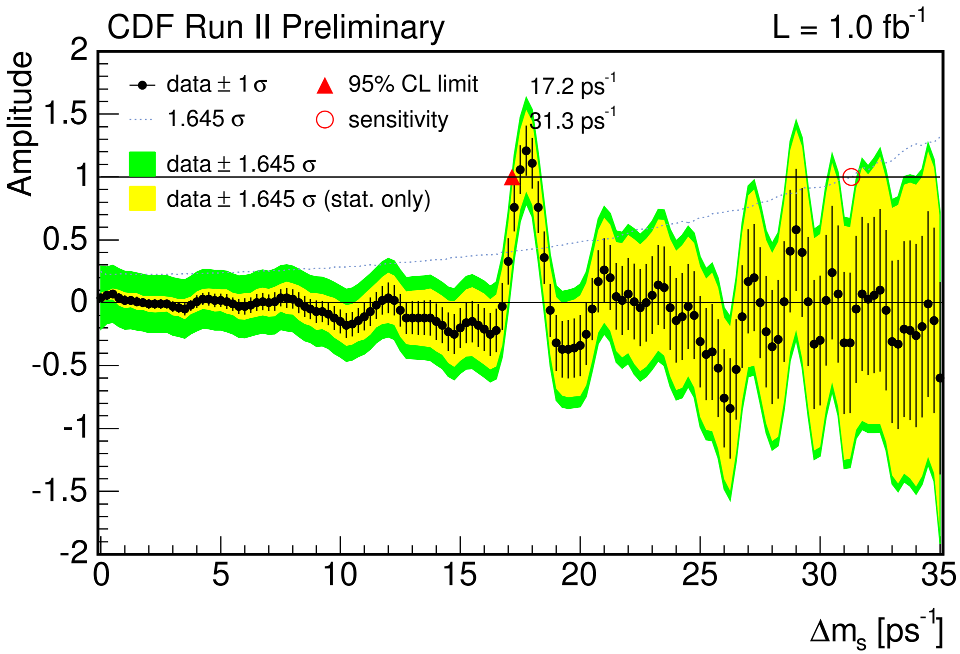

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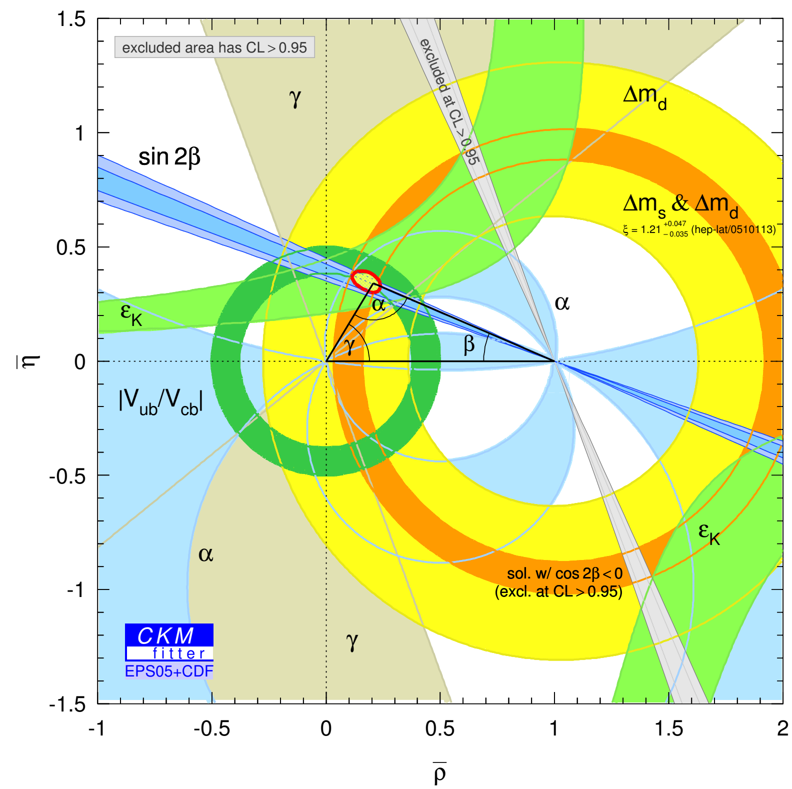
  Using $\xi_{\mathrm{LQCD}} = 1.21^{+0.047}_{-0.035}$ [HPQCD+JLQCD]

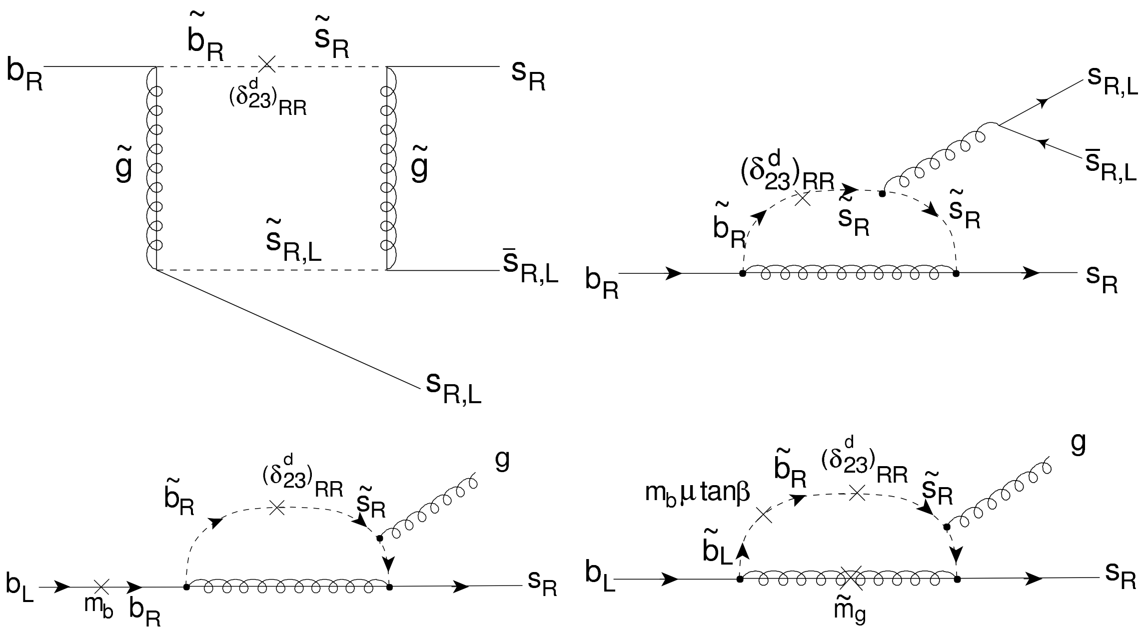


Some models to enhance Δm_s

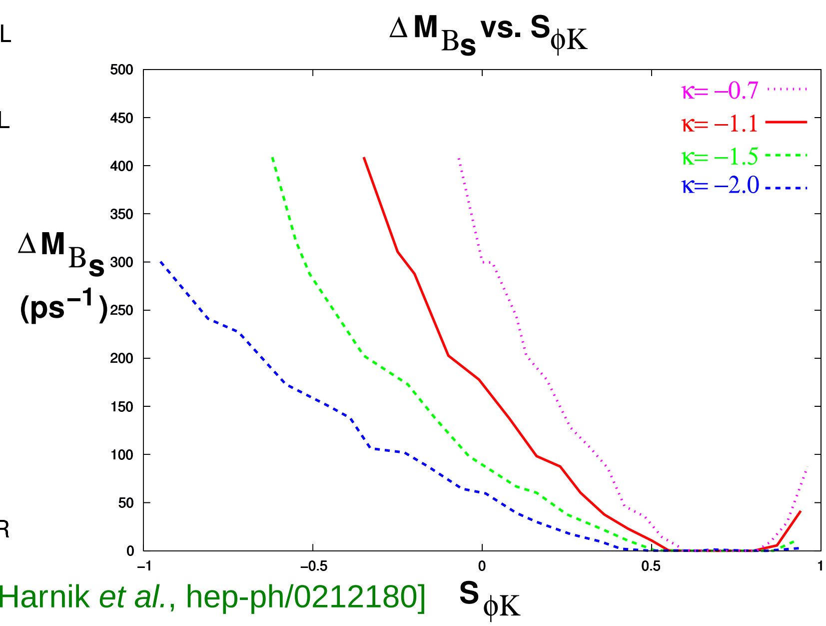
- SUSY GUTs: near-maximal $\nu_\mu - \nu_\tau$ mixing may imply large mixing between s_R and b_R, and between $\tilde{s}_R$ and $\tilde{b}_R$

  Mixing among right-handed quarks drop out from CKM matrix, but among right-handed squarks it is physical

$$\begin{pmatrix} \tilde{s}_R \\ \tilde{s}_R \\ \tilde{s}_R \\ \tilde{\nu}_\mu \\ \tilde{\mu} \end{pmatrix} \longleftrightarrow \begin{pmatrix} \tilde{b}_R \\ \tilde{b}_R \\ \tilde{b}_R \\ \tilde{\nu}_\tau \\ \tilde{\tau} \end{pmatrix}$$



$\mathcal{O}(1)$ effects in $b \to s$ possible



[Harnik *et al.*, hep-ph/0212180]

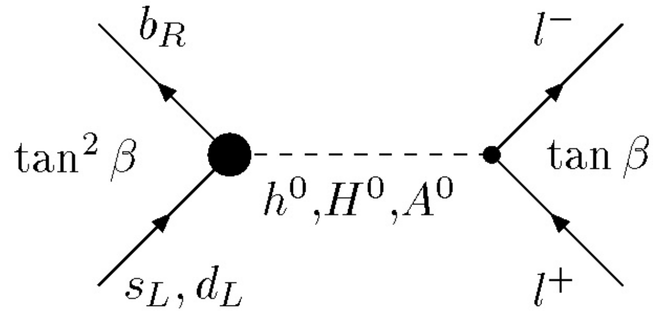
Some models to suppress Δm_s

- Neutral Higgs mediated FCNC in the large $\tan\beta$ region:

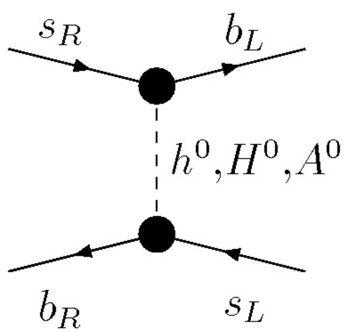
Enhancement of $\mathcal{B}(B_{d,s} \to \mu^+\mu^-) \propto \tan^6\beta$ up to two orders of magnitude above the SM

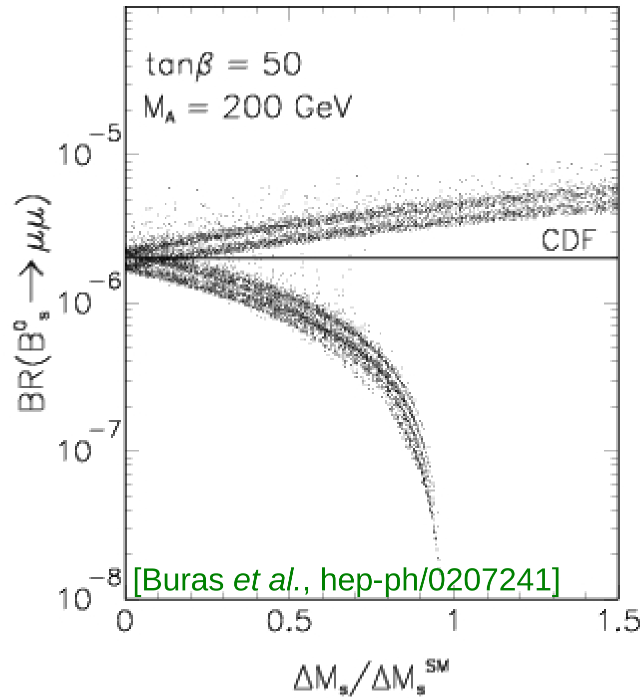
CDF: $\mathcal{B}(B_s \to \mu^+\mu^-) < 8 \times 10^{-8}$ $(90\%$ CL)

SM: 3.4×10^{-9} — measurable at LHC



Suppression of $\Delta m_s \propto \tan^4\beta$ in a correlated way

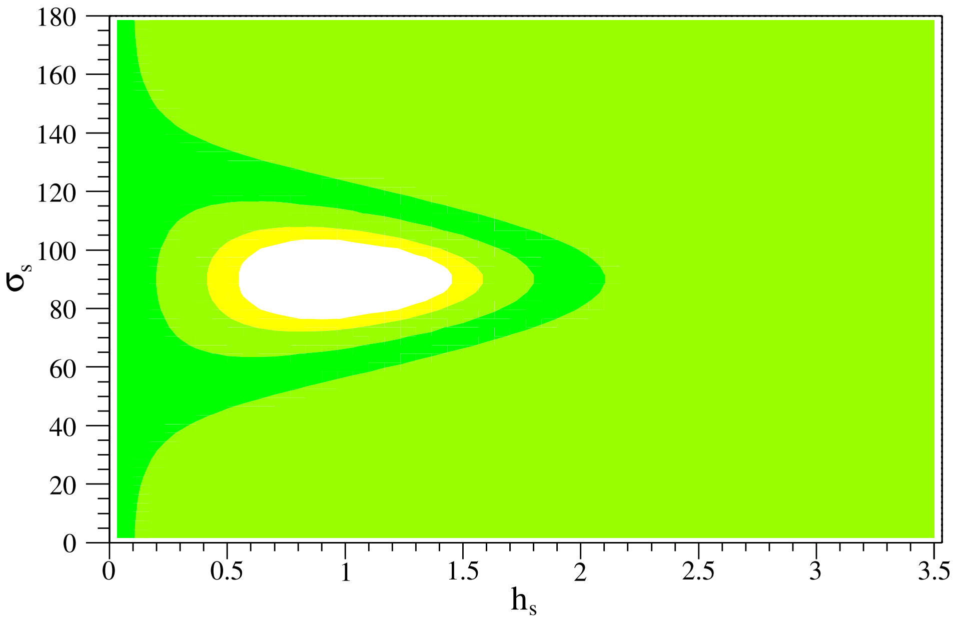


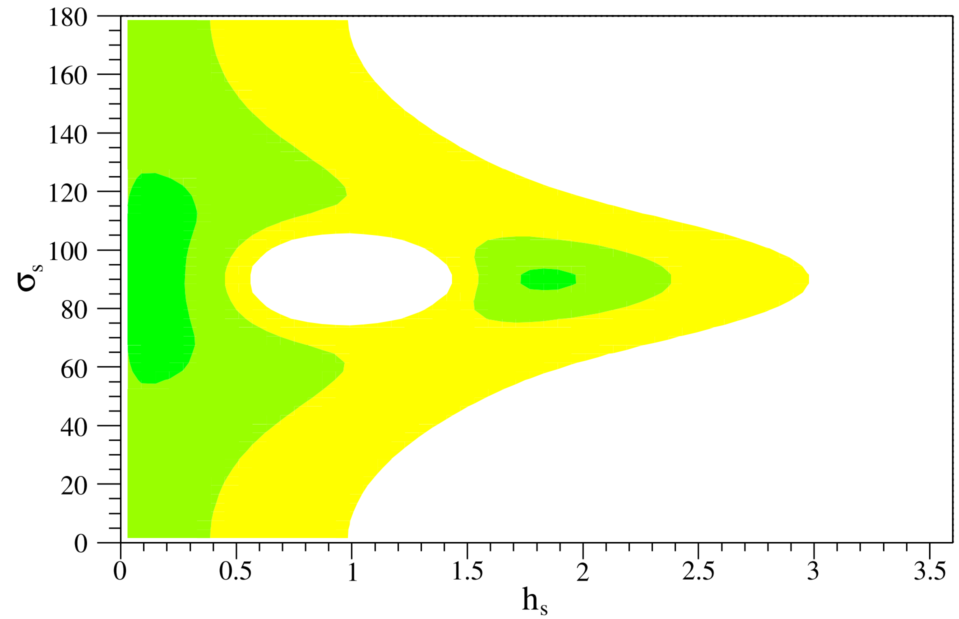


New physics in $B_s^0 \overline{B}_s^0$ mixing

- Constraints before (left) and after (right) measurement of Δm_s (and $\Delta\Gamma_s$)

  Recall parameterization: $M_{12} = M_{12}^{\rm SM}\,(1 + h_s\, e^{2i\sigma_s})$ [ZL, Papucci, Perez, hep-ph/0604112]





- To learn more about the B_s system, need data on CP asymmetry in $B_s \to J/\psi\,\phi$

  and better constraint on $A_{\rm SL}^s = \dfrac{\Gamma[\overline{B}_s^0(t)\to\ell^+X]-\Gamma[B_s^0(t)\to\ell^-X]}{\Gamma[\overline{B}_s^0(t)\to\ell^+X]+\Gamma[B_s^0(t)\to\ell^-X]}$

  [see also: Buras *et al.*, hep-ph/0604057; Grossman, Nir, Raz, hep-ph/0605028]

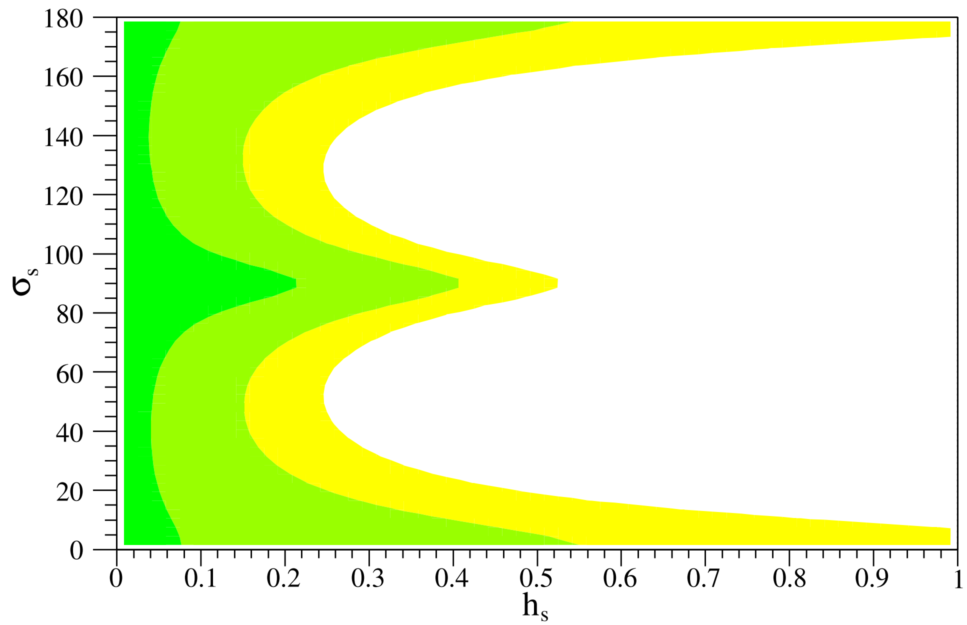
Next milestone for B_s: $S_{B_s\to\psi\phi}$

- 2000: Is $\sin 2\beta$ consistent with ϵ_K, $|V_{ub}|$ Δm_B and other constraints?
  2008: Is $\sin 2\beta_s$ consistent with ...?

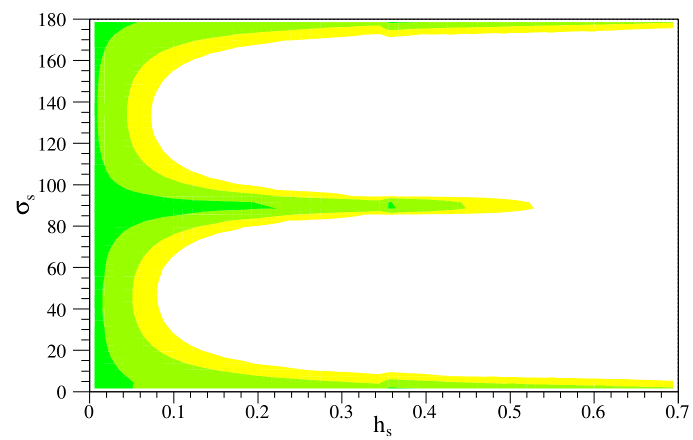
  $S_{\psi\phi}$ ($\sin 2\beta_s$ for CP-even) analog of $S_{\psi K}$
  CKM fit predicts: $\sin 2\beta_s = 0.0346^{+0.0026}_{-0.0020}$

- Plot $S_{\psi\phi} =$ SM value $\pm 0.10 \,/\, \pm 0.03$
  $0.1/1$ yr of nominal LHCb data $\Rightarrow$

- Unless there is an easy-to-find narrow resonance at ATLAS & CMS, this could be one of the most interesting early measurements



[ZL, Papucci, Perez, hep-ph/0604112]



Some recent developments

(Go from simpler to theoretically more complex)

Important features of the SM

- The SM flavor structure is very special:
  - Single source of CP violation in CC interactions
  - Suppressions due to hierarchy of mixing angles
  - Suppression of FCNC processes (loops)
  - Suppression of FCNC chirality flips by quark masses (e.g., $S_{K^*\gamma}$)

  Many suppressions that NP might not respect $\Rightarrow$ sensitivity to very high scales

- It is interesting / worthwhile / possible to test all of these

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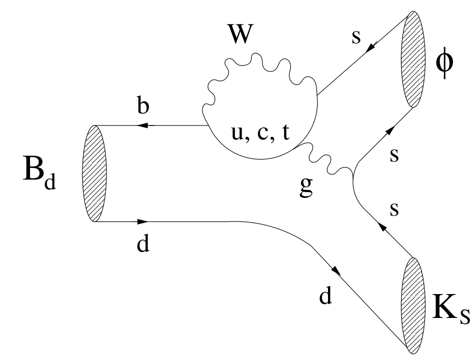
- Need broad program — there isn't just a single critical measurement

  Challenging field theory — many energy scales / expansions

CPV in $b \to s$ penguin decays

- Measuring same angle in decays sensitive to different short distance physics $\Rightarrow$ Good sensitivity to NP ($f_s = \phi K_S,\ \eta' K_S$, etc.)

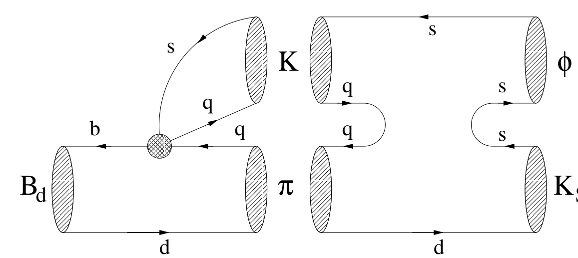
- Amplitudes with one weak phase dominate — theor. clean:



$$\overline{A} = \underbrace{V_{cb}V_{cs}^*}_{\mathcal{O}(\lambda^2)}\ \underbrace{\langle\text{“}P\text{”}\rangle}_{1} + \underbrace{V_{ub}V_{us}^*}_{\mathcal{O}(\lambda^4)}\ \underbrace{\langle\text{“}P+T_u\text{”}\rangle}_{\mathcal{O}(1)}$$

SM: expect: $S_{f_s} - S_{\psi K}$ and $C_{f_s} (= -A_{f_s}) \lesssim 0.05$

How small? Calculate $\langle\text{“}P\text{”}\rangle / \langle\text{“}P+T_u\text{”}\rangle$



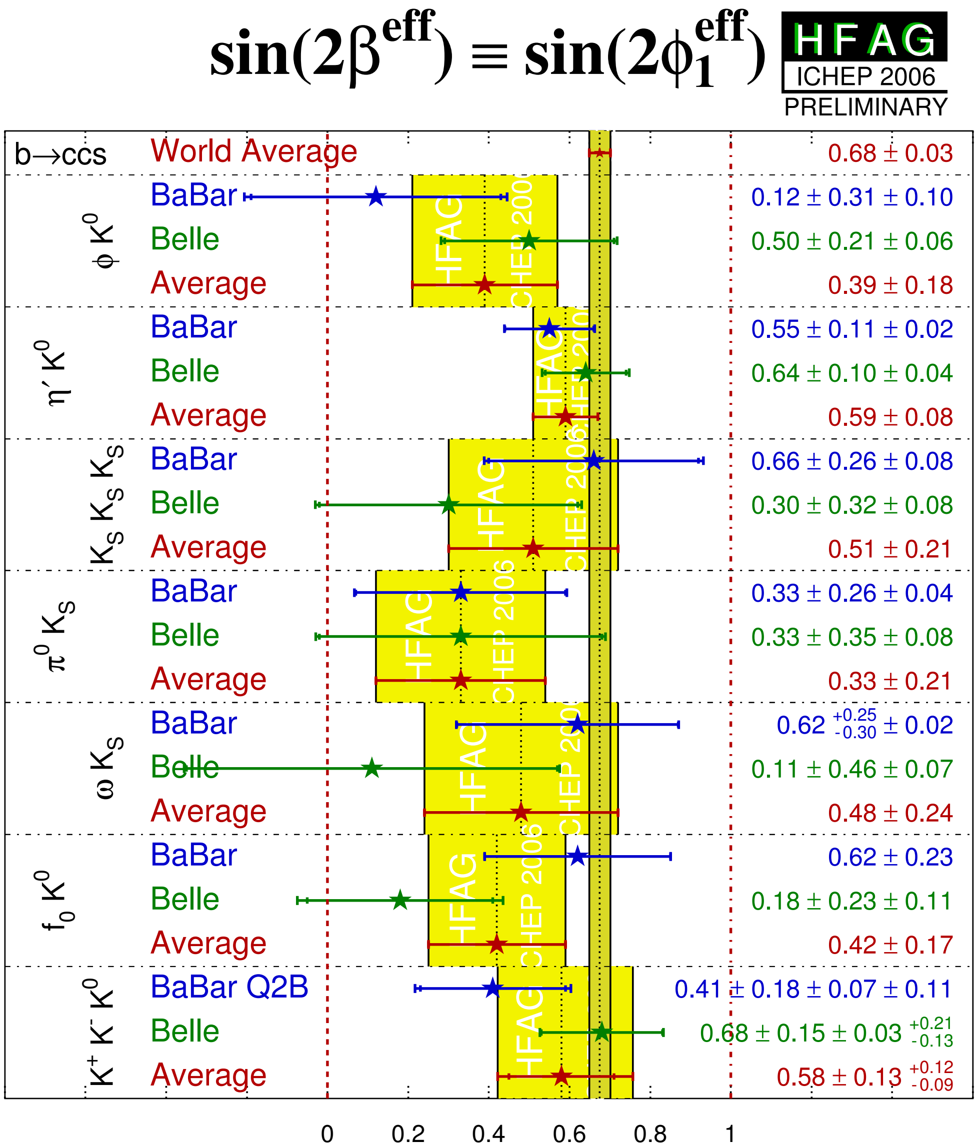
NP: $S_{f_s} \neq S_{\psi K}$ possible; expect mode-dependent S_f

Depend on size & phase of SM and NP amplitude

NP could enter $S_{\psi K}$ mainly in mixing, while S_{f_s} through both mixing and decay

- Interesting to pursue independent of present results — there is room for NP

Is there NP in $b \to s$ transitions?



- SM: expect $S_{f_s} - S_{\psi K} \lesssim 0.05$
  NP: $S_{f_s} \neq S_{\psi K}$ possible (mode-dep.)
- Significance of deviations from $S_{\psi K}$ decreased — most modes still $<$ SM
  Will any of them become significant?
- Smallest exp. errors: $\eta' K_S$ and ϕK_S
  All calculations find $<$ few $\times\, 0.01$ SM pollution [Buchalla *et al.*; Beneke; Williamson & Zupan]
- Improved theory may allow in future to constrain specific NP models / parameters via pattern of deviations

α from $B \to \rho\rho,\ \pi\pi,\ \rho\pi$

- $S_{\rho^+\rho^-} = \sin[(B\text{-mix} = -2\beta) + (\overline{A}/A = -2\gamma + \ldots) + \ldots] = \sin(2\alpha) + \text{small}$

  (1) Longitudinal polarization (CP-even) dominates

  (2) Small rate: $\mathcal{B}(B \to \rho^0\rho^0) = (1.16 \pm 0.46) \times 10^{-6}$ $\Rightarrow$ small $\Delta\alpha$

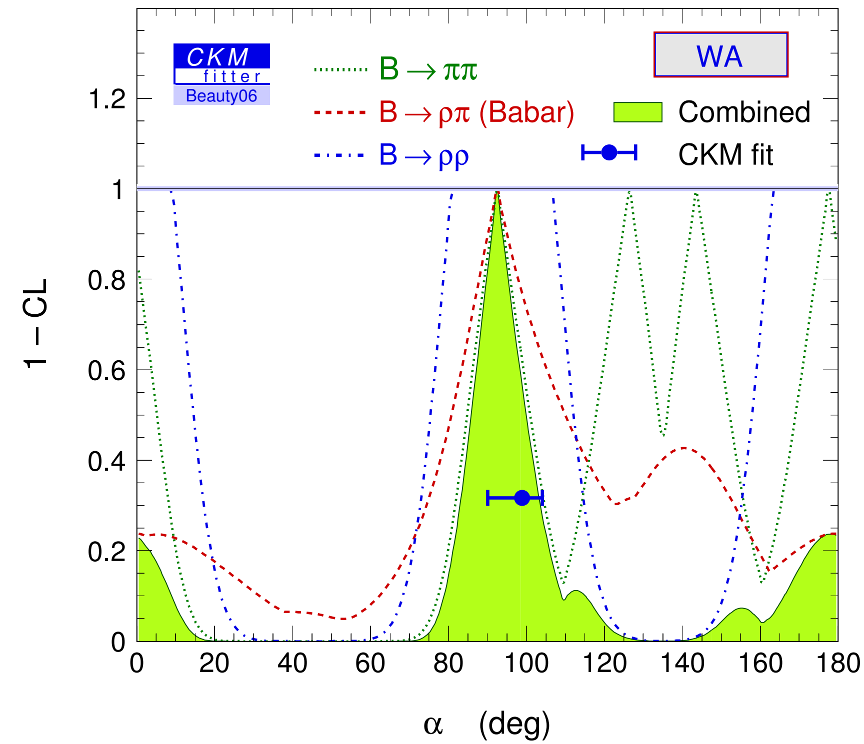
  $\frac{\mathcal{B}(B\to\pi^0\pi^0)}{\mathcal{B}(B\to\pi^+\pi^0)} = 0.23 \pm 0.04$ vs. $\frac{\mathcal{B}(B\to\rho^0\rho^0)}{\mathcal{B}(B\to\rho^+\rho^0)} = 0.06 \pm 0.03$ — observed in 2006

- Before 2006 $B \to \rho\rho$ dominated

  All three modes important now

  $\rho\rho$ is more complicated than $\pi\pi$, $I = 1$ possible due to $\Gamma_\rho \neq 0$; its $\mathcal{O}(\Gamma_\rho^2/m_\rho^2)$ effects can be constrained with more data [Falk *et al.*]

- All measurements combined: $\alpha = (93^{+11}_{-9})^\circ$



γ from $B^\pm \to DK^\pm$

- Tree level: interfere $b \to c \; (B^- \to D^0 K^-)$ and $b \to u \; (B^- \to \overline{D}^0 K^-)$
  Need $D^0, \overline{D}^0 \to$ same final state; determine B and D decay amplitudes from data

  Sensitivity driven by: $r_B = |A(B^- \to \overline{D}^0 K^-)/A(B^- \to D^0 K^-)| \sim 0.1 - 0.2$

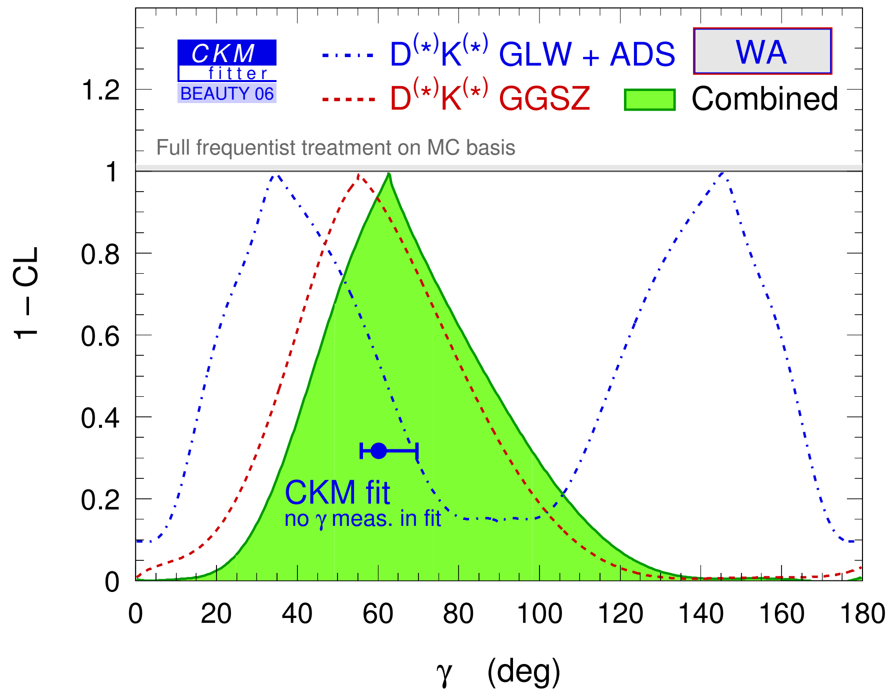
  Central value of r_B decreased in 2006

- Before 2006 Dalitz plot analysis in $D^0, \overline{D}^0 \to K_S \pi^+ \pi^-$ dominated [Giri *et al.*; Bondar]

  Variants according to D decay; comparable results now

- All measurements combined: $\gamma = (62^{+38}_{-24})^\circ$

  $\Rightarrow$ Need a lot more data



inclusive processes

B physics has been fertile ground for theoretical developments:

HQET, ChPT, SCET, Lattice QCD, ...

Remark: hadronic uncertainties

- To believe discrepancy $=$ new physics, need model independent predictions:

$$\text{Quantity of interest} = (\text{calculable prefactor}) \times \Big[1 + \sum_k (\text{small parameters})^k\Big]$$

Theoretical uncertainty is parametrically suppressed by $\sim$ (small parameter)^N, but models may be used to estimate the uncertainty

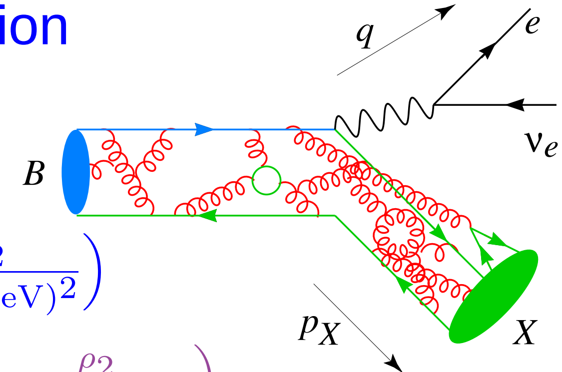
- Most of the recent progress comes from expanding in powers of Λ/m_Q, $\alpha_s(m_Q)$

... a priori not known whether $\Lambda \sim 200\text{MeV}$ or $\sim 2\text{GeV}$ $(f_\pi, m_\rho, m_K^2/m_s)$

... need experimental guidance to see which cases work how well

Determination of $|V_{cb}|$ from $B \to X_c \ell \bar{\nu}$

- Theoretically cleanest application of heavy quark expansion



$$\Gamma(B \to X_c \ell \bar{\nu}) = \frac{G_F^2 |V_{cb}|^2}{192\pi^3} \left(\frac{m_\Upsilon}{2}\right)^5 (0.534) \times \Bigg[1$$
$$- 0.22 \left(\frac{\Lambda_{1S}}{500\text{ MeV}}\right) - 0.011 \left(\frac{\Lambda_{1S}}{500\text{ MeV}}\right)^2 - 0.052 \left(\frac{\lambda_1}{(500\text{ MeV})^2}\right) - 0.071 \left(\frac{\lambda_2}{(500\text{ MeV})^2}\right)$$
$$- 0.006 \left(\frac{\lambda_1 \Lambda_{1S}}{(500\text{ MeV})^3}\right) + 0.011 \left(\frac{\lambda_2 \Lambda_{1S}}{(500\text{ MeV})^3}\right) - 0.006 \left(\frac{\rho_1}{(500\text{ MeV})^3}\right) + 0.008 \left(\frac{\rho_2}{(500\text{ MeV})^3}\right)$$
$$+ 0.011 \left(\frac{T_1}{(500\text{ MeV})^3}\right) + 0.002 \left(\frac{T_2}{(500\text{ MeV})^3}\right) - 0.017 \left(\frac{T_3}{(500\text{ MeV})^3}\right) - 0.008 \left(\frac{T_4}{(500\text{ MeV})^3}\right)$$
$$+ 0.096\epsilon - 0.030\epsilon^2_{\rm BLM} + 0.015\epsilon \left(\frac{\Lambda_{1S}}{500\text{ MeV}}\right) + \dots \Bigg]$$

[Bauer, ZL, Luke, Manohar, Trott; Buchmuller & Flacher]

Corrections: $\mathcal{O}(\Lambda/m)$: $\sim 20\%$, $\mathcal{O}(\Lambda^2/m^2)$: $\sim 5\%$, $\mathcal{O}(\Lambda^3/m^3)$: $\sim 1-2\%$,
$\mathcal{O}(\alpha_s)$: $\sim 10\%$, Unknown terms: $< 2\%$

~ 90 observables: consistent fit to hadronic matrix elements and $|V_{cb}|$; test theory

Clear evidence for power suppressed corrections — measure λ_1 with $\lesssim 15\%$ error

- $|V_{cb}| = (41.7 \pm 0.7) \times 10^{-3}$, $< 2\%$ error; also determine m_b and m_c

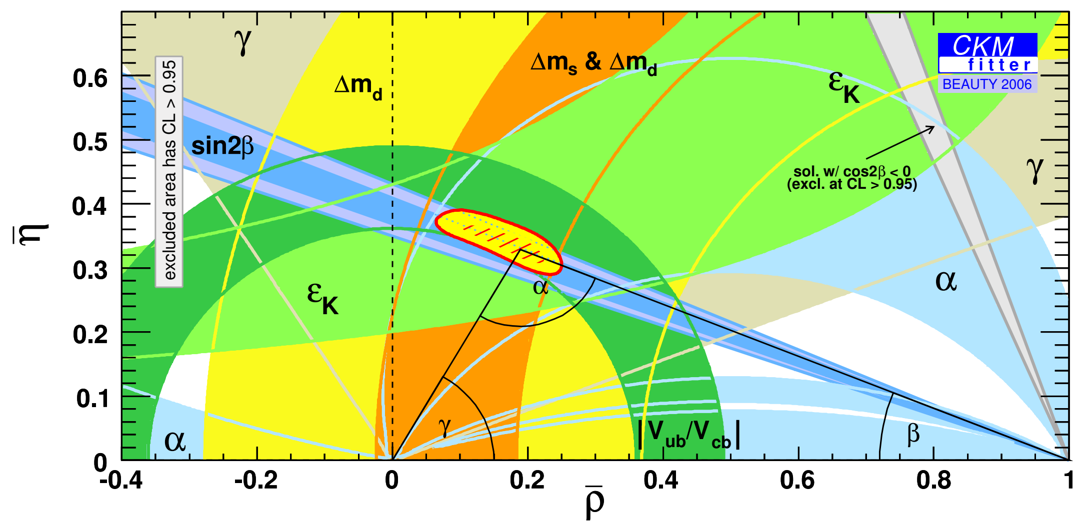
$|V_{ub}|$ from inclusive $B \to X_u \ell \bar{\nu}$

- Phase space cuts required to suppress $b \to c\ell\bar{\nu}$ background complicate theory:
  Lower scales, dependence on nonperturbative functions (rather than numbers)

  Renormalization of shape function and structure of subleading terms complicated
  [Bauer & Manohar; Bosch, Lange, Neubert, Paz; Lee & Stewart; etc.]

  "B-beam" technique $+$ use of several kinematic variables: E_ℓ, m_X, q^2, P_+

- Inclusive average $|V_{ub}| = (4.49 \pm 0.19 \pm 0.27) \times 10^{-3}$ $>$ CKM fit $(3.7 \pm 0.1) \times 10^{-3}$



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- Inclusive average $|V_{ub}| = (4.49 \pm 0.19 \pm 0.27) \times 10^{-3}$ $>$ CKM fit $(3.7 \pm 0.1) \times 10^{-3}$

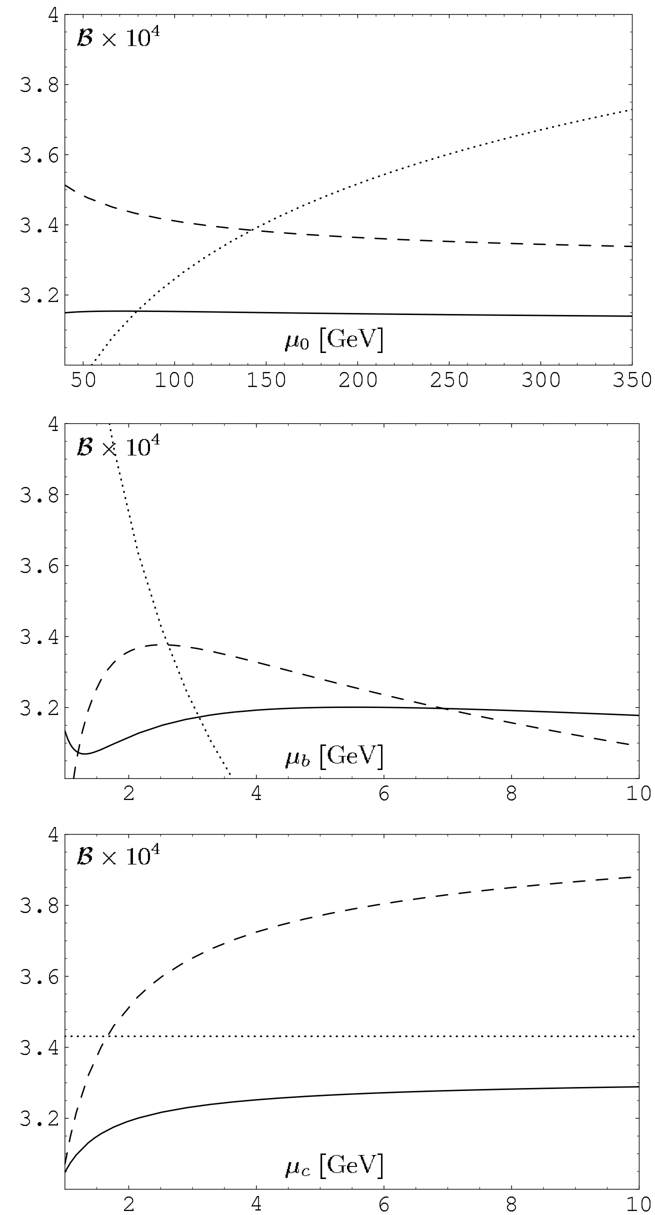
- Exclusive determinations from $B \to \pi\ell\nu$ lower (larger errors)
  - Lattice QCD ($q^2 > 16\,\mathrm{GeV}^2$): $|V_{ub}| = (3.7 \pm 0.3^{+0.6}_{-0.4}) \times 10^{-3}$ [HPQCD & FNAL]
  - Lattice & dispersion relation: $|V_{ub}| = (4.0 \pm 0.5) \times 10^{-3}$ [Arnesen et al.; Becher & Hill]
  - Light-cone SR: $|V_{ub}| = (3.4 \pm 0.1^{+0.6}_{-0.4}) \times 10^{-3}$ [Ball, Zwicky; Braun *et al.*; Colangelo, Khodjamirian]

- Statistical fluctuation? Inclusive average optimistic? Something more interesting?

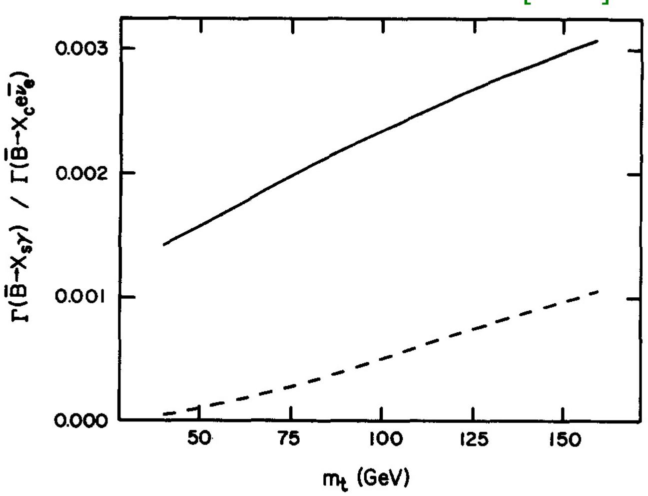
  Understanding the $B \to \pi\ell\bar{\nu}$ form factor also important for $B \to \pi\pi,\ K\pi$ decays

Inclusive $B \to X_s\gamma$

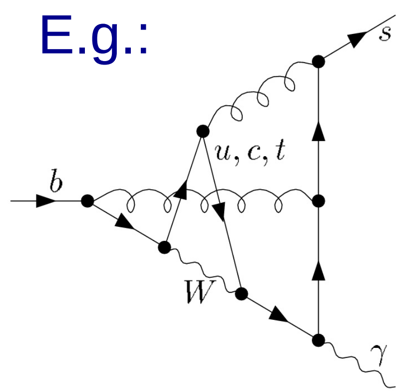
- One (if not "the") most elaborate SM calculations
  Constrains many models: 2HDM, SUSY, LRSM, etc.
- NNLO practically completed [Misiak et al., hep-ph/0609232]
  4-loop running, 3-loop matching and matrix elements
  Scale dependences significantly reduced $\Rightarrow$
- $\mathcal{B}(B \to X_s\gamma)\big|_{E_\gamma>1.6\mathrm{GeV}} = (3.15 \pm 0.23) \times 10^{-4}$
  measurement: $(3.55 \pm 0.26) \times 10^{-4}$



B. Grinstein et al. / $\bar{B}$-meson decay [1990]



E.g.:



$B \to X_s\gamma$ and neutralino dark matter

- Green: excluded by $B \to X_s\gamma$

  Brown: excluded (charged LSP)

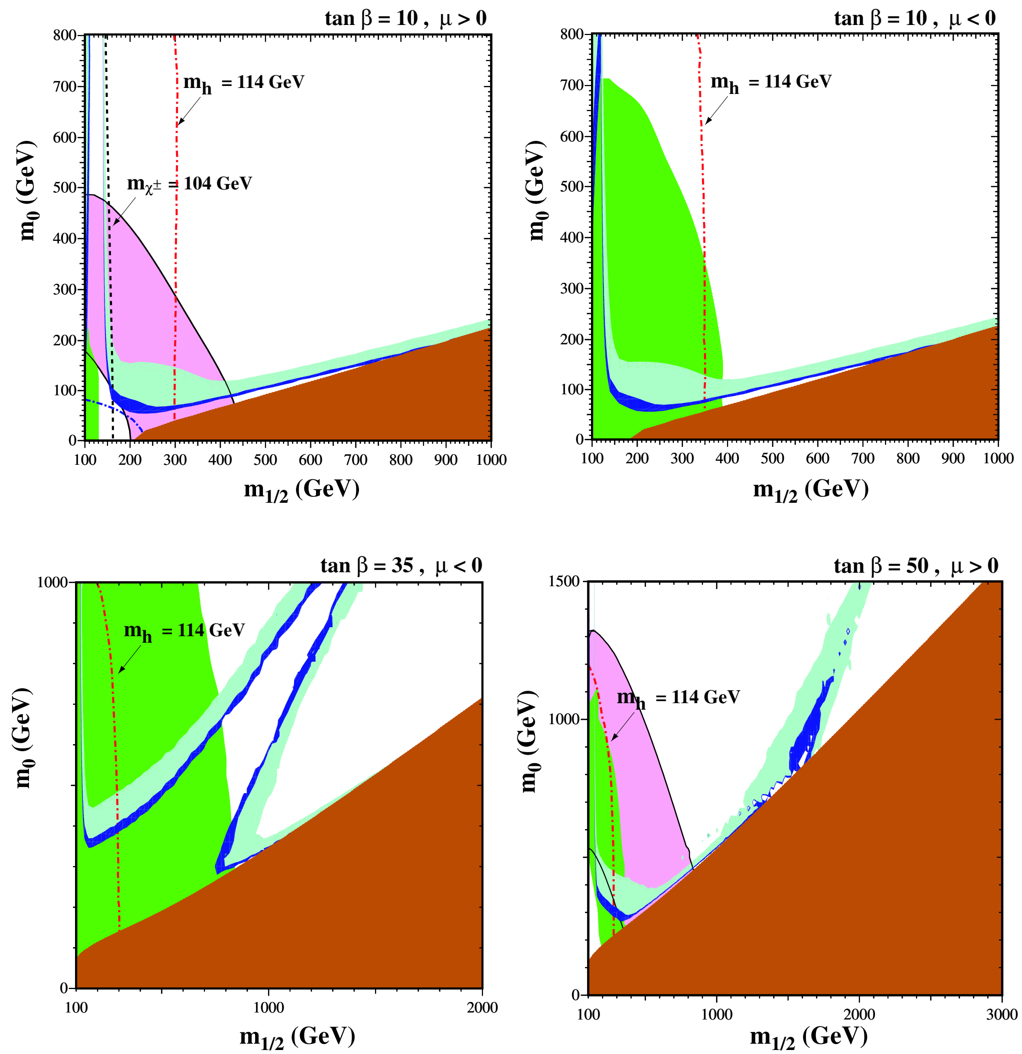
  Magenta: favored by $g_\mu - 2$

  Blue: favored by $\Omega_\chi h^2$ from WMAP

- Analyses assume constrained MSSM

  If either $S_{\eta' K} \neq \sin 2\beta$ or $S_{K^*\gamma} \neq 0$, then has to be redone

  Then $B \to X_s \ell^+ \ell^-$ and $B_s \to \mu\mu$ may give complementary constraints



[Ellis, Olive, Santoso, Spanos]

Inclusive $B \to X_s \ell^+ \ell^-$

- Rate depends on

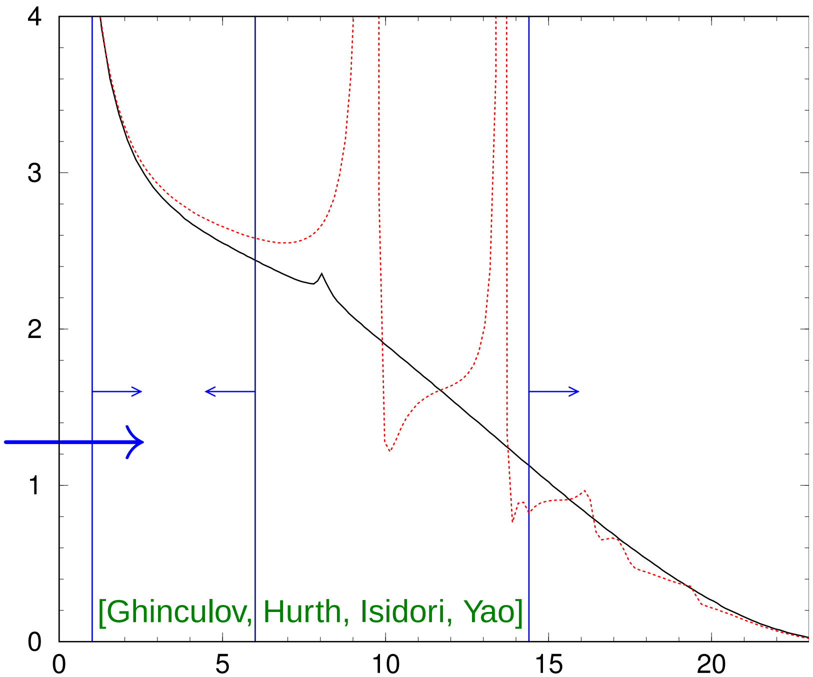
$$O_7 = m_b \, \bar{s} \sigma_{\mu\nu} e F^{\mu\nu} P_R b,$$

$$O_9 = e^2 (\bar{s} \gamma_\mu P_L b)(\bar{\ell} \gamma^\mu \ell),$$

$$O_{10} = e^2 (\bar{s} \gamma_\mu P_L b)(\bar{\ell} \gamma^\mu \gamma_5 \ell)$$

Theory most precise for $1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2$

Experiments need additional cut $m_{X_s} \lesssim 2\,\mathrm{GeV}$
to suppress $b \to c(\to s \ell^+ \nu) \ell^- \bar{\nu}$ background



- Rate in this region is determined by B light-cone distribution function ("shape fn")
Theory similar to measurement of $|V_{ub}|$ from $B \to X_u \ell \bar{\nu}$ (and related to $B \to X_s \gamma$)

[Lee, ZL, Stewart, Tackmann]

- Sensitivity to NP survives after taking into account hadronic effects

A "new" observable in $B \to X_s \ell^+ \ell^-$

$$\frac{d^2\Gamma}{ds\, dz} \sim 3\Gamma_0 (1-s)^2 \Big\{ (1+z^2) \Big[\Big(\mathcal{C}_9 + \frac{2}{s}\mathcal{C}_7\Big)^2 + \mathcal{C}_{10}^2 \Big] \qquad H_T \quad [\Gamma = H_T + H_L]$$

$$- 4\, z\, s\, \mathcal{C}_{10} \Big(\mathcal{C}_9 + \frac{2}{s}\mathcal{C}_7\Big) \qquad H_A \quad [\equiv (4/3) A_{\mathrm{FB}}]$$

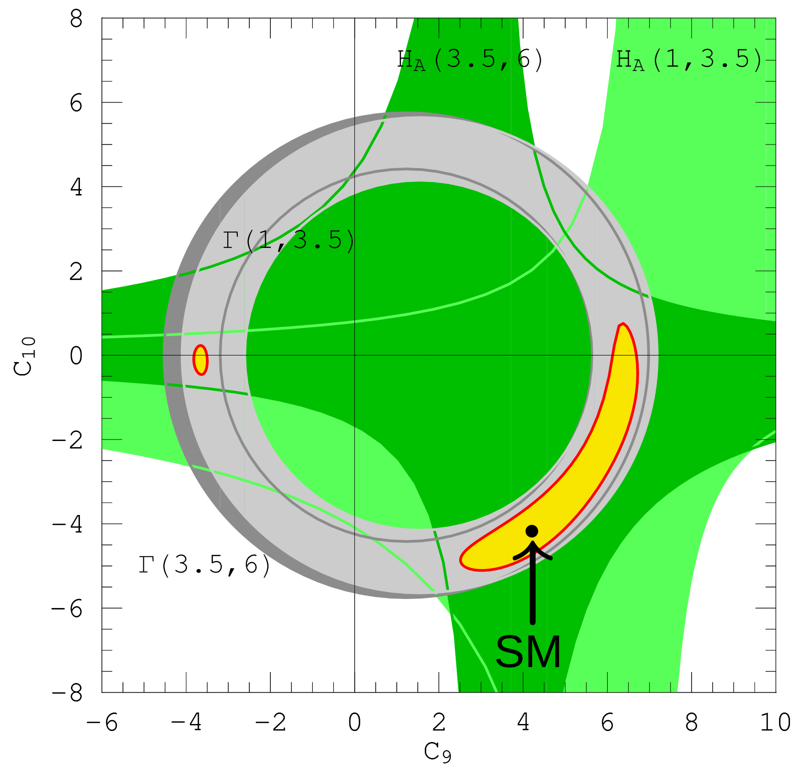
$$+ (1-z^2) \Big[(\mathcal{C}_9 + 2\mathcal{C}_7)^2 + \mathcal{C}_{10}^2 \Big] \Big\} \qquad H_L \quad [\text{no } \mathcal{C}_7/s \text{ pole}]$$

$z = \cos[\angle(\vec{p}_{\ell^+}, \vec{p}_{\bar{B}^0, B^-})]$ [or $(\vec{p}_{\ell^-}, \vec{p}_{B^0, B^+})$] in $\ell^+\ell^-$ center of mass frame

- Inclusive, with "guessed" errors for $\sim 1\,\mathrm{ab}^{-1}$

  Define: $H_i(q_1^2, q_2^2) = \int_{q_1^2}^{q_2^2} dq^2\, H_i(q^2)$

- Small q^2-dependence $\Rightarrow$ splitting Γ into two regions not useful (splitting $H_A \equiv A_{\mathrm{FB}}$ is!)



[Lee, ZL, Stewart, Tackmann, hep-ph/0612156]

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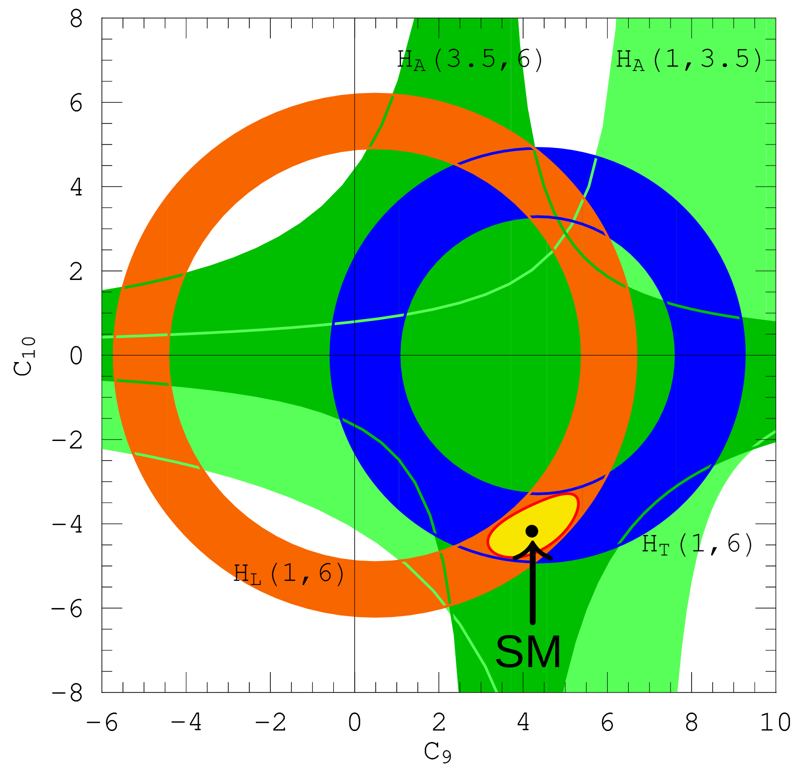
- Separating H_T and H_L (q^2-indept) very powerful



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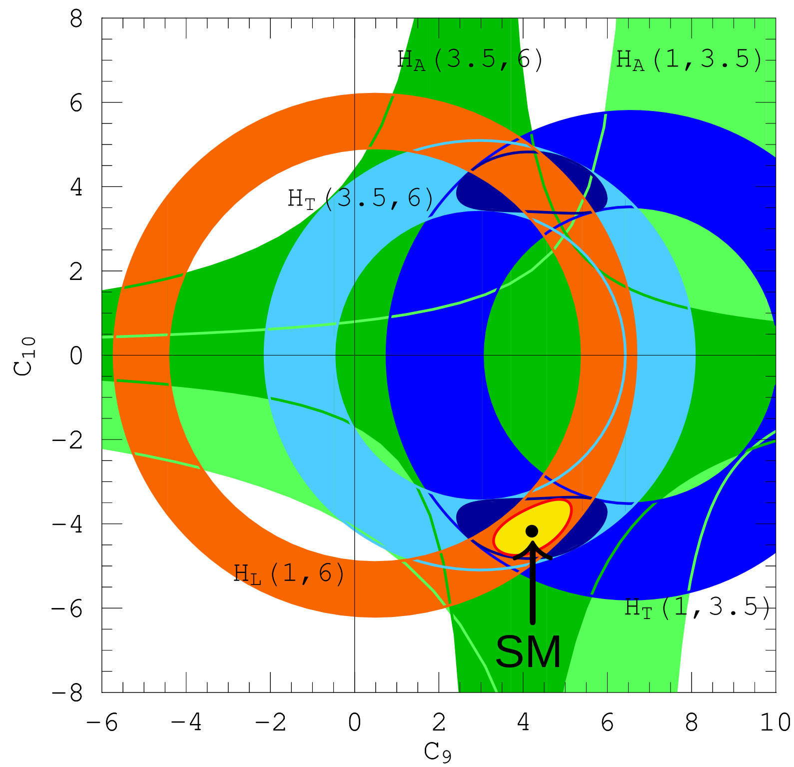
- Small q^2-dependence $\Rightarrow$ splitting Γ into two regions not useful (splitting $H_A \equiv A_{\rm FB}$ is!)
- Separating H_T and H_L (q^2-indept) very powerful
- Can extract all info from a few integrated rates

[Lee, ZL, Stewart, Tackmann, hep-ph/0612156]



Many other interesting rare B decays

- Important probes of new physics
  - $B \to K^*\gamma$ or $X_s\gamma$: Best $m_{H^\pm}$ limits in 2HDM — in SUSY many param's
  - $B \to K^{(*)}\ell^+\ell^-$ or $X_s\ell^+\ell^-$: bsZ penguins, SUSY, right handed couplings

A crude guide ($\ell = e$ or μ)

Decay	$\sim$ SM rate	physics examples
$B \to s\gamma$	3×10^{-4}	$\lvert V_{ts}\rvert$, $H^\pm$, SUSY
$B \to \tau\nu$	1×10^{-4}	$f_B \lvert V_{ub}\rvert$, $H^\pm$
$B \to s\nu\nu$	4×10^{-5}	new physics
$B \to s\ell^+\ell^-$	5×10^{-6}	new physics
$B_s \to \tau^+\tau^-$	1×10^{-6}	
$B \to s\tau^+\tau^-$	5×10^{-7}	$\vdots$
$B \to \mu\nu$	5×10^{-7}	
$B_s \to \mu^+\mu^-$	4×10^{-9}	
$B \to \mu^+\mu^-$	2×10^{-10}	

Replacing $b \to s$ by $b \to d$ costs a factor ~ 20 (in SM); interesting to test in both: rates, CP asymmetries, etc.

In $B \to q\, l_1\, l_2$ decays expect 10–20% K^*/ρ, and 5–10% K/π (model dept)

Many of these (cleanest inclusive ones) impossible at hadron colliders

Nonleptonic decays: the Λ_b lifetime

- OPE has been thought to be less reliable in non-leptonic than semileptonic decay (local duality)

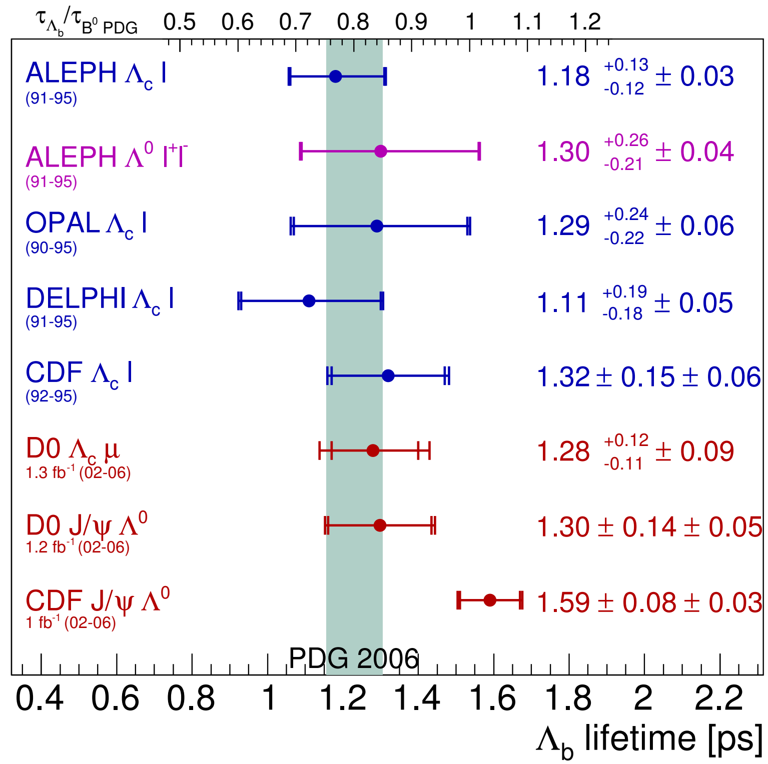
  Prediction Data (PDG)

$$\frac{\tau_{\Lambda_b}}{\tau_{B^0}} = 1 + \mathcal{O}\left(\frac{\Lambda^2}{m_b^2}, 16\pi^2 \frac{\Lambda^3}{m_b^3}\right) = 0.80 \pm 0.05$$

  Hard to accommodate $\tau_{\Lambda_b}/\tau_{B^0}$ much below 0.9

  [Bigi *et al.*; Neubert & Sachrajda; Gabbiani, Onishchenko, Petrov, ...]

  Recent CDF measurement $\sim 3\sigma$ from PDG



- How this settles will affect our estimate of the uncertainty of the calculation of $\Delta\Gamma_s$

  (In addition to perturbative uncertainty and that in matrix elements [from LQCD])

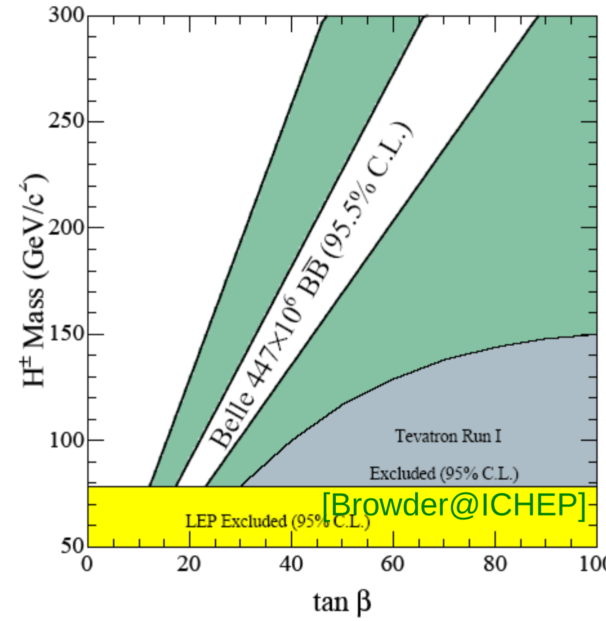
Aside: measurement of $B \to \tau\nu$

- A new operator not previously constrained

  Sensitive to tree-level charged Higgs contribution

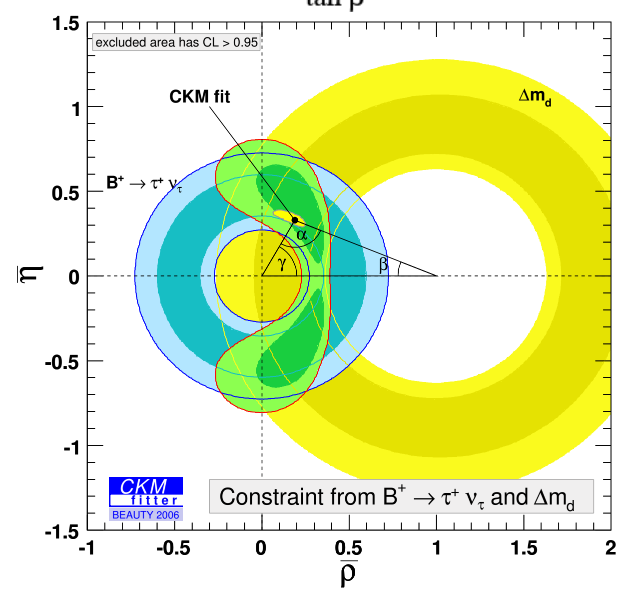
  Data: $\mathcal{B}(B^+ \to \tau^+\nu) = (1.34 \pm 0.48) \times 10^{-4}$

  To constrain SM, need much more precise $\Gamma(B \to \tau\nu)$



- If experimental error small: $\Gamma(B \to \tau\nu)/\Delta m_d$ determines $|V_{ub}/V_{td}|$ independent of f_B (left with B_d error)

- If error of f_B small: two circles that intersect at $\alpha \sim 90°$



- With a super-B-factory (+LHCb+CLEO-c), a Grinstein-type double ratio can minimize uncertainties:

$$\frac{\mathcal{B}(B \to \ell\bar{\nu})}{\mathcal{B}(B_s \to \ell^+\ell^-)} \times \frac{\mathcal{B}(D_s \to \ell\bar{\nu})}{\mathcal{B}(D \to \ell\bar{\nu})} = \text{calculable to few \%}$$

exclusive processes

Two-body nonleptonic B decays

- Huge field: some successes of factorization, some unexplained phenomena
- $B \to D\pi, D\rho$: a testing ground (important also for measuring "$2\beta + \gamma$")
  $\mathcal{B}(B^- \to D^{(*)0}\pi^-)/\mathcal{B}(\overline{B}^0 \to D^{(*)+}\pi^-) \sim 1.8 \pm 0.2$ ... also for ρ
- $B \to \pi\pi$: measure α — rates and CPV not easy to explain (are exp's consistent?)
  $C_{\pi^+\pi^-} = -0.39 \pm 0.07\,, \quad \mathcal{B}(B \to \pi^0\pi^0)/\mathcal{B}(B \to \pi^+\pi^0) = 0.23 \pm 0.04$
- $B \to K\pi$: P–T interference sensitive to γ — data looked puzzling (disappearing?)

$$R_c \equiv 2\,\frac{\mathcal{B}(B^+ \to \pi^0 K^+) + \mathcal{B}(B^- \to \pi^0 K^-)}{\mathcal{B}(B^+ \to \pi^+ K^0) + \mathcal{B}(B^- \to \pi^- \overline{K}^0)} = 1.11 \pm 0.07, \quad R_n \equiv \frac{1}{2}\,\frac{\mathcal{B}(B^0 \to \pi^- K^+) + \mathcal{B}(\overline{B}^0 \to \pi^+ K^-)}{\mathcal{B}(B^0 \to \pi^0 K^0) + \mathcal{B}(\overline{B}^0 \to \pi^0 \overline{K}^0)} = 0.99 \pm 0.07$$

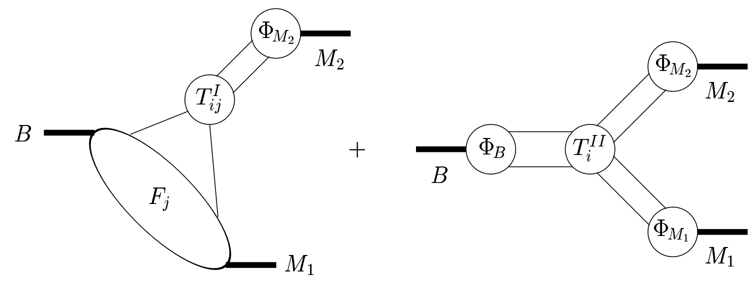
$$R_L \equiv 2\,\frac{\bar\Gamma(B^- \to \pi^0 K^-) + \bar\Gamma(\overline{B}^0 \to \pi^0 \overline{K}^0)}{\bar\Gamma(B^- \to \pi^- \overline{K}^0) + \bar\Gamma(\overline{B}^0 \to \pi^+ K^-)} = 1.06 \pm 0.05$$

- Another topic: $B \to VV$ polarization (won't talk about)
- Literally, hundreds of papers on each... SM and NP "explanations"

Factorization in charmless $B \to M_1 M_2$

- BBNS (QCDF) proposal [Beneke, Buchalla, Neubert, Sachrajda]

$$\langle \pi\pi | O_i | B \rangle \sim F_{B\to\pi}\, T(x) \otimes \phi_\pi(x) + T(\xi, x, y) \otimes \phi_B(\xi) \otimes \phi_\pi(x) \otimes \phi_\pi(y)$$



- KLS (pQCD) proposal involve only ϕ_B & $\phi_{M_{1,2}}$, with $k_\perp$ dependence [Keum, Li, Sanda]

- SCET: $\langle \pi\pi | O_i | B \rangle \sim A_{c\bar{c}} + \sum_{ij} T(x, y) \otimes \left[J_{ij}(x, z_k, k_\ell^+) \otimes \phi_\pi^i(z_k)\, \phi_B^j(k_\ell^+) \right] \otimes \phi_\pi(y)$

- In practice, relate some convolutions to the measurable $B \to M_{1,2}$ form factors
Selfconsistency between many nonleptonic (and/or semileptonic) rates

Open issues — theoretical challenges:

– Is the second term suppressed by α_s compared to the first one?

– Are charm penguins perturbatively calculable?

– Role and regularization of certain seemingly divergent convolutions?

SCET in a nutshell

- Effective field theory for processes involving energetic hadrons, $E \gg \Lambda$

  [Bauer, Fleming, Luke, Pirjol, Stewart, + . . .]

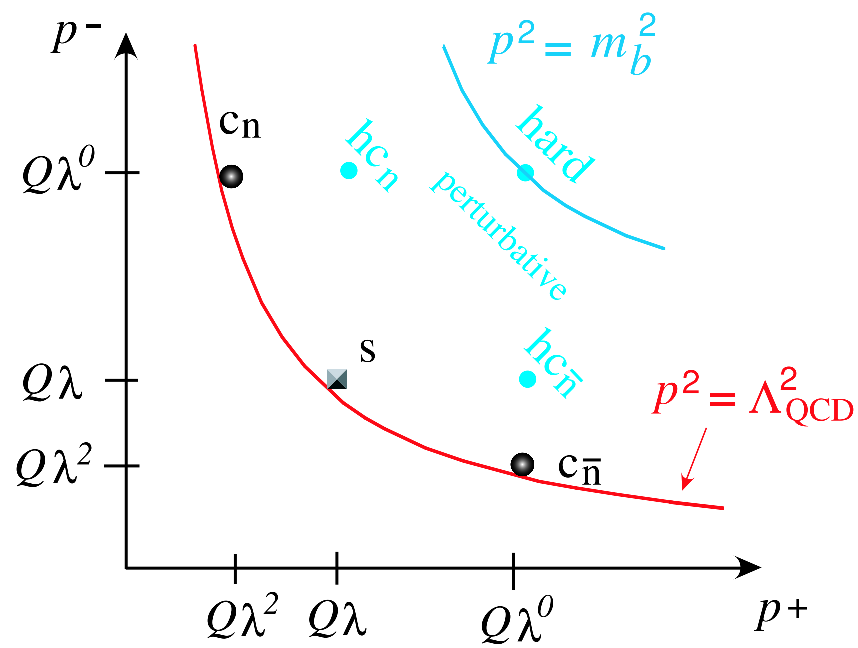
- Expand in $\Lambda^2 \ll \Lambda E \ll E^2$, separate scales [light-cone variables: $(p_-, p_+, p_\perp)$]

  Introduce distinct fields for relevant degrees of freedom; power counting in λ

  SCET$_\mathrm{I}$: $\lambda = \sqrt{\Lambda/E}$ — jets $(m \sim \Lambda E)$

  SCET$_\mathrm{II}$: $\lambda = \Lambda/E$ — hadrons $(m \sim \Lambda)$

  New symmetries: collinear / soft gauge inv.



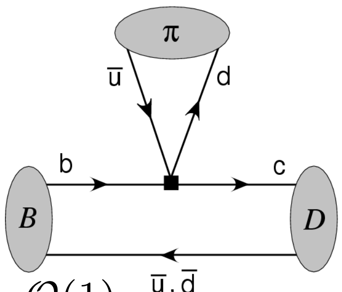
- Simplified / new $(B \to D\pi, \pi\ell\bar\nu)$ proofs of factorization theorems [Bauer, Pirjol, Stewart]

- Subleading order untractable before: factorization in $B \to D^0\pi^0$ [Mantry, Pirjol, Stewart], CPV parameter $S_{K^*\gamma}$ [Grossman, Grinstein, ZL, Pirjol], weak annihilation, etc.

A breakthrough in nonleptonic B decays

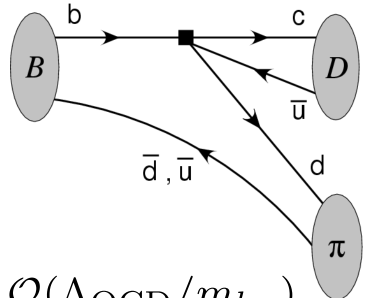
- SCET: factorization proven in $B \to DM$(light) to all orders in α_s & leading in Λ/m

$D^+\pi^-$, $D^0\pi^-$



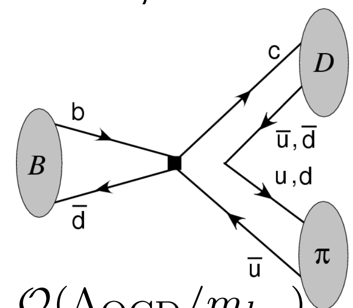
SCET: $\mathcal{O}(1)$

$D^0\pi^-$, $D^0\pi^0$



$\mathcal{O}(\Lambda_{\rm QCD}/m_{b,c})$

$D^+\pi^-$, $D^0\pi^0$



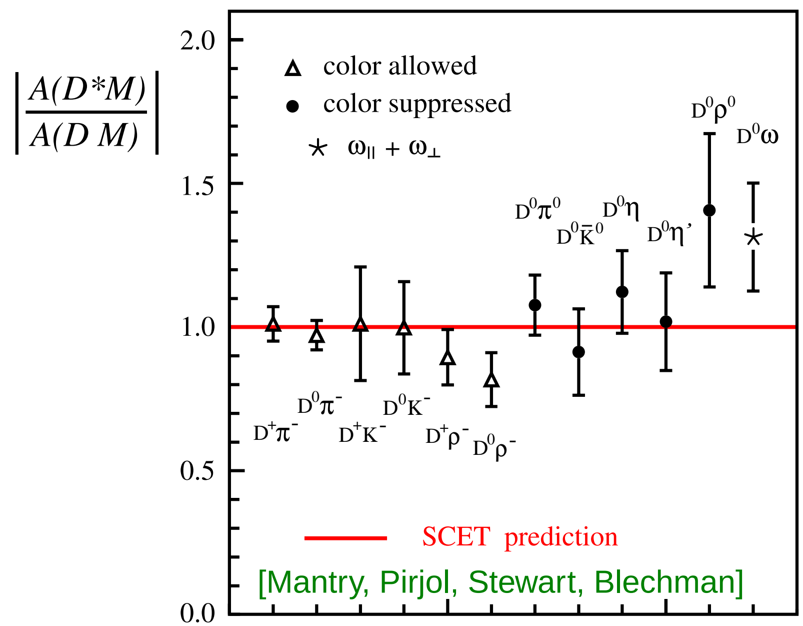
$\mathcal{O}(\Lambda_{\rm QCD}/m_{b,c})$

- $D^*\pi/D\pi$ ratios: the $\triangle = 1$ relations follow from naive factorization and heavy quark symmetry

  The $\bullet = 1$ relations do not — a prediction of SCET not foreseen by any model calculations

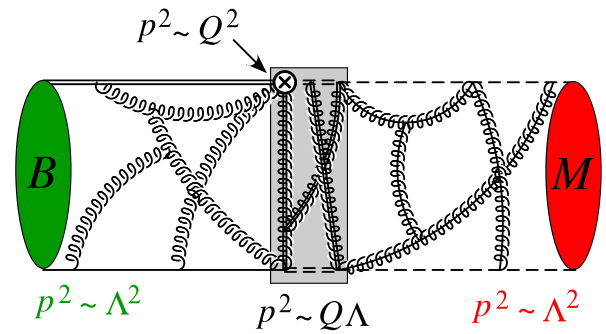
- Also predicts equal strong phases between $I = 1/2$ and $3/2$ amplitudes in $D\pi$ and $D^*\pi$

  Data: $\delta(D\pi) = (28 \pm 3)^\circ$, $\delta(D^*\pi) = (32 \pm 5)^\circ$



Semileptonic $B \to \pi, \rho$ form factors

- At leading order in Λ/Q, to all orders in α_s, two contributions at $q^2 \ll m_B^2$: soft form factor & hard scattering
  (Separation scheme dependent; $Q = E, m_b$, omit μ's)
  [Beneke & Feldmann; Bauer, Pirjol, Stewart; Becher, Hill, Lange, Neubert]



$$F(Q) = C_i(Q)\,\zeta_i(Q) + \frac{m_B f_B f_M}{4E^2} \int \mathrm{d}z\mathrm{d}x\mathrm{d}k_+\, T(z,Q)\; J(z,x,k_+,Q)\; \phi_M(x)\phi_B(k_+)$$

- Symmetries $\Rightarrow$ nonfactorizable (1st) term obey form factor relations [Charles *et al.*]
  $3\ B \to P$ and $7\ B \to V$ form factors related to 3 universal functions

---

- Relative size? QCDF: 2nd $\sim \alpha_s \times$(1st), PQCD: 1st $\ll$ 2nd, SCET: 1st $\sim$ 2nd

- Whether first term factorizes (involves $\alpha_s(\mu_i)$, as 2nd term does) involves same physics issues as hard scattering, annihilation, etc., contributions to $B \to M_1 M_2$

An application: $B \to \rho\gamma$

- Determines $|V_{td}/V_{ts}|$ independent of $B\overline{B}$ mixing (a new operator!)

  Hadronic physics: form factor at $q^2 = 0$ [Bosch, Buchalla; Beneke, Feldman, Seidel; Ali, Lunghi, Parkhomenko]

$$\frac{\mathcal{B}(B \to \rho\gamma)}{\mathcal{B}(B \to K^*\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \left(\frac{m_B - m_\rho}{m_B - m_{K^*}}\right)^3 \begin{cases} \frac{1}{2}(\xi_{V^0\gamma})^{-2} \\ (\xi_{V^\pm\gamma})^{-2} \end{cases}$$

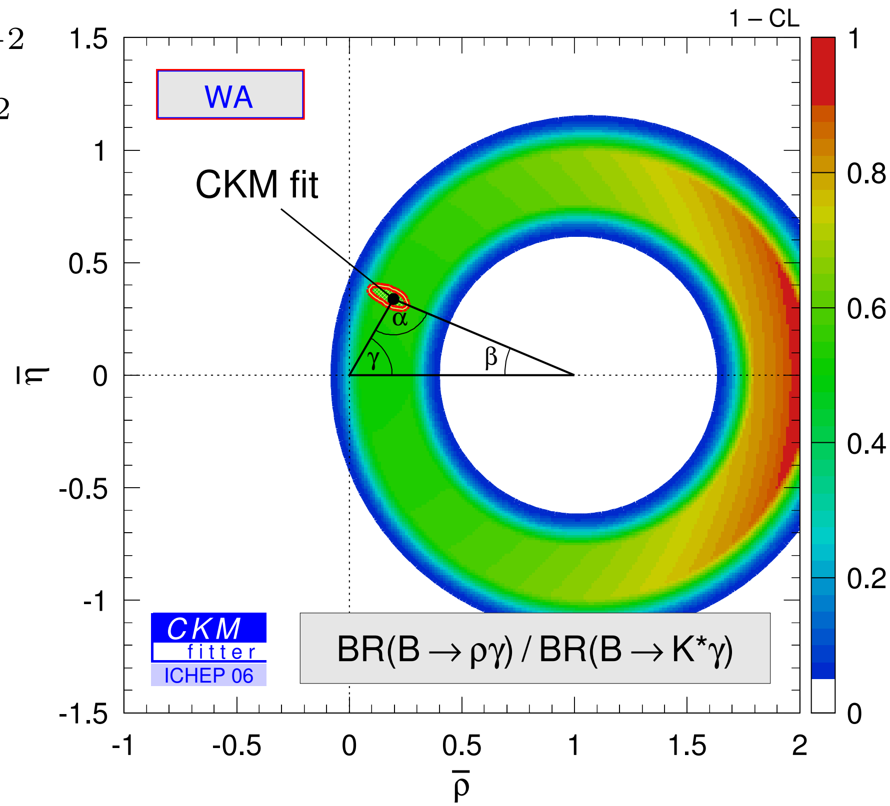
  No weak annihilation in B^0, cleaner than $B^\pm$
  (Please don't average $\rho\gamma$ and $\omega\gamma$!)

  $SU(3)$ breaking: $\xi = 1.2 \pm 0.1$ (CKM '05)

  [Ball, Zwicky; Becirevic; Mescia]

  Conservative? $\xi - 1$ is model dependent

  Could LQCD help? Moving NRQCD?



- More data: control some theoretical errors by comparing ratios in B^0 vs. $B^\pm$ decay

Meet the "zero-bin"

- Encounter singular integrals $\int_0^1 \mathrm{d}x\, \phi_\pi(x)/x^2 \sim \int \mathrm{d}x/x$ in several calculations

  e.g., $B \to \pi$ form factor, weak annihilation, "chirally enhanced" terms, etc.

  Divergences $\sim$ one of the quarks become soft near $x = 0$ or 1 (p_i^- small), but derivations use that they are collinear (p_i^- large)

- Zero-bin: simple way to eliminate double counting between collinear & soft modes

  (collinear quark with $p_i^- = 0$ is not a collinear quark) [Manohar & Stewart, hep-ph/0605001]

  Understand which singularities are physical, and how confinement effects them

- Zero-bin ensures there is no contribution from $x_i = p_i^-/(\bar{n} \cdot p_\pi) \sim 0$

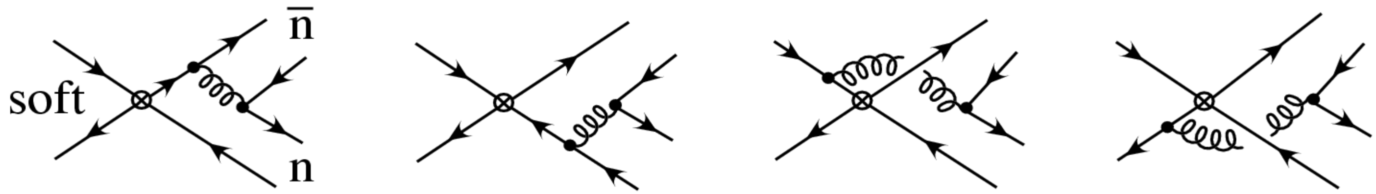
  Subtractions implied by zero-bin depend on the singularity of integrals, e.g.:

$$\int_0^1 \frac{\mathrm{d}x}{x^2}\, \phi_\pi(x,\mu) \;\Rightarrow\; \int_0^1 \mathrm{d}x\, \frac{\phi_\pi(x,\mu) - x\, \phi_\pi'(0,\mu)}{x^2} + \phi_\pi'(0,\mu) \ln\left(\frac{\bar{n}\cdot p_\pi}{\mu_-}\right) + \ldots$$

$= \text{finite and real}$

Weak annihilation

- Power suppressed,
  order Λ/E corrections



Yields convolution integrals of the form: $\int_0^1 \mathrm{d}x\, \phi_\pi(x)/x^2\,, \quad \phi_\pi(x) \sim 6x(1-x)$

Singularity if gluon near on-shell — one of the pions near endpoint configuration

- KLS: first emphasized importance for strong phases and CPV [Keum, Li, Sanda]
  Divergence rendered finite by $k_\perp$, still sizable and complex contributions

- BBNS: interpret as IR sensitivity $\Rightarrow$ model by complex parameters
  $$\text{“}X_A\text{”} = \int_0^1 dx/x = (1 + \rho_A e^{i\varphi_A}) \ln(m_B/\Lambda)$$ [Beneke, Buchalla, Neubert, Sachrajda]

- SCET: Match onto six-quark operators of the form
  $$O_{1d}^{(ann)} = \sum_q \underbrace{\left[\bar{d}_s \Gamma_s\, b_v\right]}_{\text{gives } f_B} \underbrace{\left[\bar{u}_{\bar{n},\omega_2} \Gamma_{\bar{n}}\, q_{\bar{n},\omega_3}\right]}_{\pi \text{ in } \bar{n} \text{ direction}} \underbrace{\left[\bar{q}_{n,\omega_1} \Gamma_n\, u_{n,\omega_4}\right]}_{\pi \text{ in } n \text{ direction}}$$ [Arnesen, ZL, Rothstein, Stewart]

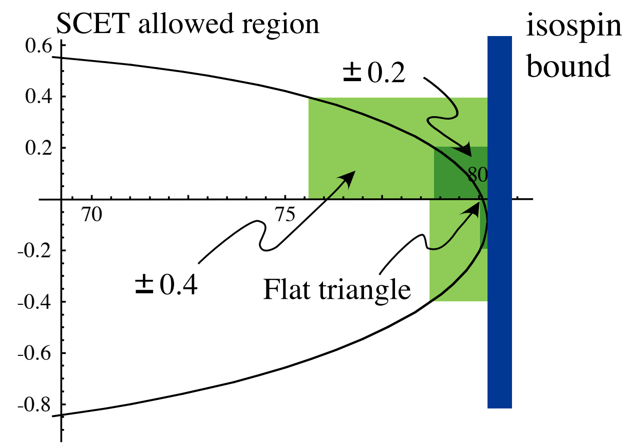
  At leading nonvanishing order in Λ/m_b and α_s: real and calculable

What the $B \to \pi\pi$ data tell us

- Theory predicts suppression of strong phase: $\arg(T/C) = \mathcal{O}(\alpha_s, \Lambda/m_b)$
- Use theory to extract weak phase [Bauer, Stewart, Rothstein]

  SCET fit to data: $\gamma \sim 80^\circ$, about 2σ from CKM fit

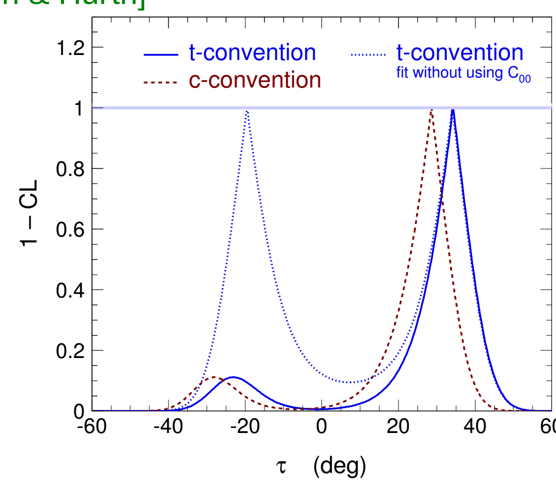
  Statistics? Power corrections? New physics?



- Use CKM fit to learn about theory [Grossman, Hocker, ZL, Pirjol; Feldmann & Hurth]

  – large power corrections to T, C?
  – large u penguins?
  – large weak annihilation?
  – conspiracy between several smaller effects?

  Need to better understand $B \to \pi\pi$, $B \to \pi\ell\bar{\nu}$, $\alpha_{\rho\rho}$, γ_{DK}



- $K\pi$: hard to accommodate $A_{K^+\pi^0} = 0.047 \pm 0.026$, given $A_{K^+\pi^-} = -0.093 \pm 0.015$

More hints of possible surprises

- Theory of heavy-to-light decays is rapidly developing

  More work and data needed to understand behavior of expansions
  Why some predictions work at $\lesssim 10\%$ level, while others receive $\sim 30\%$ corrections

  Open issues: role of charming penguins, chirally enhanced terms, annihilation, ...

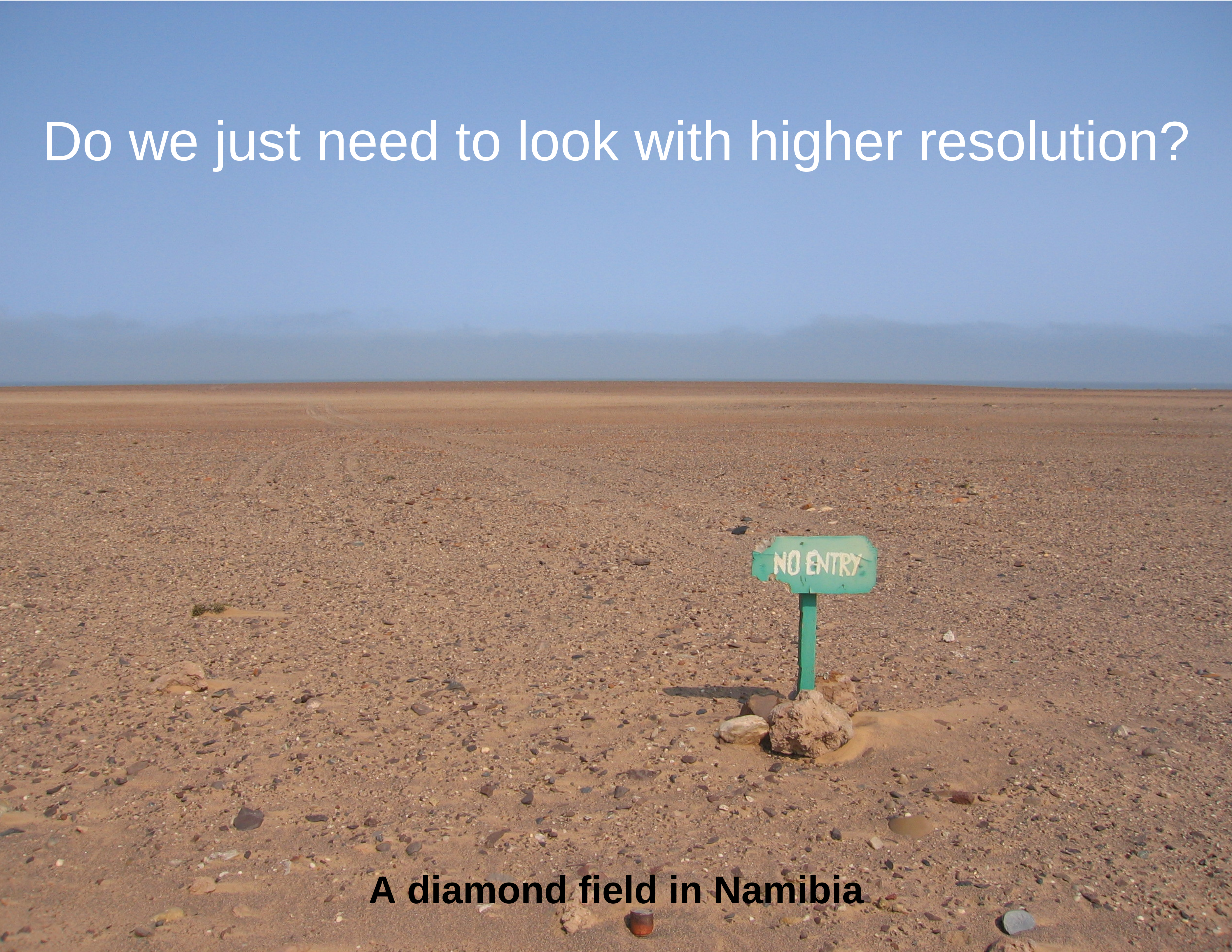
  We have the tools to try to address the questions

- Hope to clarify in the next 2–3 years (better data + refined theory)
  - $B \to \pi\pi,\ K\pi$ rates and CP asymmetries
  - α from $B \to \pi\pi$ using SCET vs. α from CKM fit
  - $B \to VV$ polarization
  - Robustness of predictions for $S_{K^*\gamma}$ and zero of $A_{\rm FB}$ in $B \to K^*\ell^+\ell^-$

Final comments


Shall we see new physics in flavor physics?
NO ENTRY

Do we just need to look with higher resolution?



A diamond field in Namibia

Outlook

- If there are new particles at TeV scale, new flavor physics could show up any time
- Goal for flavor physics experiments:

  If NP is seen in flavor physics: study it in as many different operators as possible

  If NP is not seen in flavor physics: achieve what is theoretically possible
  could teach us a lot about the NP seen at LHC

  The program as a whole is a lot more interesting than any single measurement
- Try to distinguish: One / many sources of CPV?
  CPV only in CC interactions?
  NP couples mostly to up / down sector?
  $\ldots$ to 3rd or all generations? $\Delta(F) = 2$ or / and 1?
- Many interesting measurements, complementarity with high energy frontier

Theoretical limitations (continuum methods)

- Many interesting decay modes will not be theory limited for a long time

Measurement (in SM)	Theoretical limit	Present error
$S_{\psi K}\ \ (\beta)$	$\sim 0.2^\circ$	1.0°
$S_{\eta' K},\ S_{\phi K}$ (β)	$\sim 2^\circ$	$6^\circ,\ 11^\circ$
$S_{K_S\pi^0\gamma}$ (related to β)	$\sim 5^\circ$	$\sim 15^\circ$
$B\to\rho\rho,\ \rho\pi,\ \pi\pi\ \ (\alpha)$	$\sim 1^\circ$	$\sim 15^\circ$
$B\to DK\ \ (\gamma)$	$\ll 1^\circ$	$\sim 25^\circ$
$B_s\to\psi\phi\ \ (\beta_s)$	$\sim 0.2^\circ$	—
$B_s\to D_s K\ \ (\gamma-2\beta_s)$	$\ll 1^\circ$	—
$\lvert V_{cb}\rvert$	$\sim 1\%$	$\sim 2\%$
$\lvert V_{ub}\rvert$	$\sim 5\%$	$\sim 10\%$
$B\to X_s\gamma$	$\sim 5\%$	$\sim 10\%$
$B\to X_s\ell^+\ell^-$	$\sim 5\%$	$\sim 20\%$
$B\to K^{(*)}\nu\bar\nu$	$\sim 5\%$	—

For some entries, the shown theoretical limits require more complicated analyses

Conclusions

- Our knowledge of the flavor sector and CPV improved tremendously

  CKM phase is the dominant source of CPV in flavor changing processes

- Deviations from SM in B_d mixing, $b \to s$ and even in $b \to d$ decays are constrained

  NP in loop-induced transitions may still be $\sim 0.3 \times$SM (sensitive to scales $\gg$ LHC)

- Progress in theory toward model independently understanding more observables:

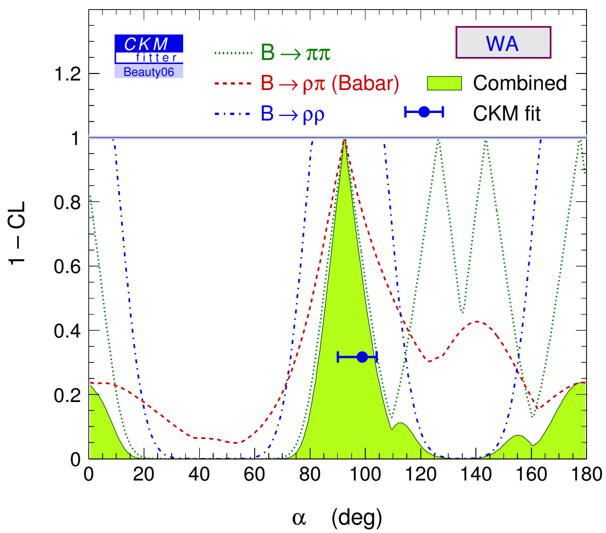
  Precision calculations for inclusive semileptonic and rare decays

  Zero-bin $\Rightarrow$ no divergent convolutions, annihilation real (novel ideas)

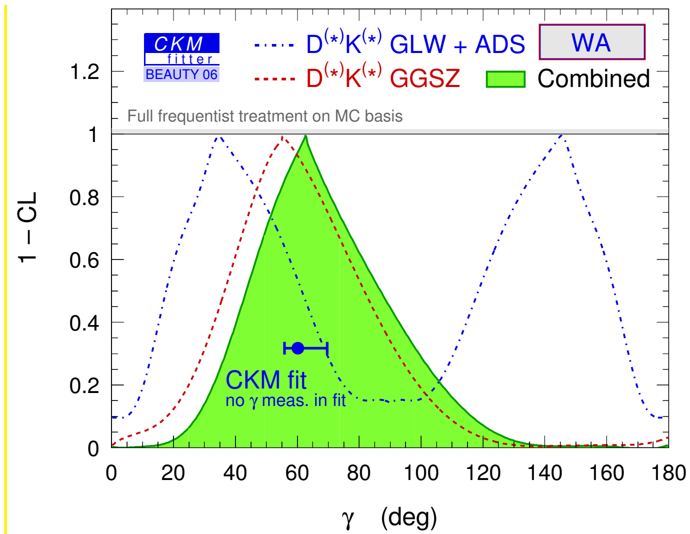
- Flavor physics may provide clues to model building in the LHC era

Backup slides

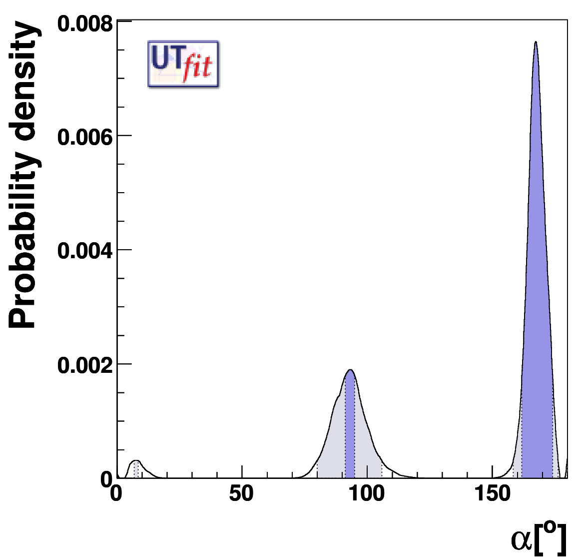
Aside: statistics



$$\alpha = (93^{+11}_{-9})^\circ$$



$$\gamma = (62^{+38}_{-24})^\circ$$

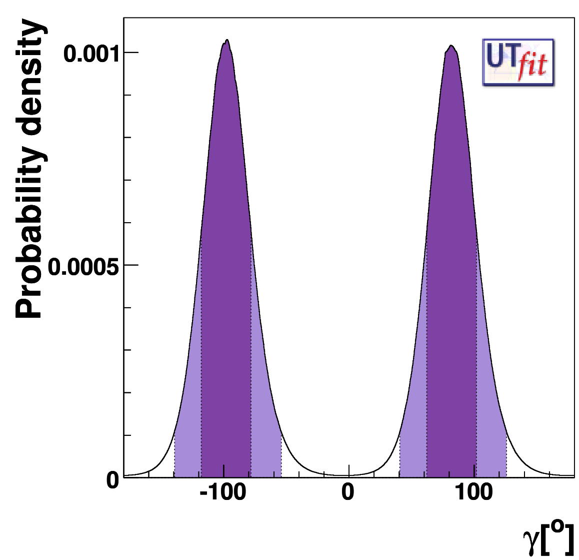


Favored sol'n:

$$\alpha = (168 \pm 6)^\circ$$

SM region:

$$\alpha = (92 \pm 7)^\circ$$



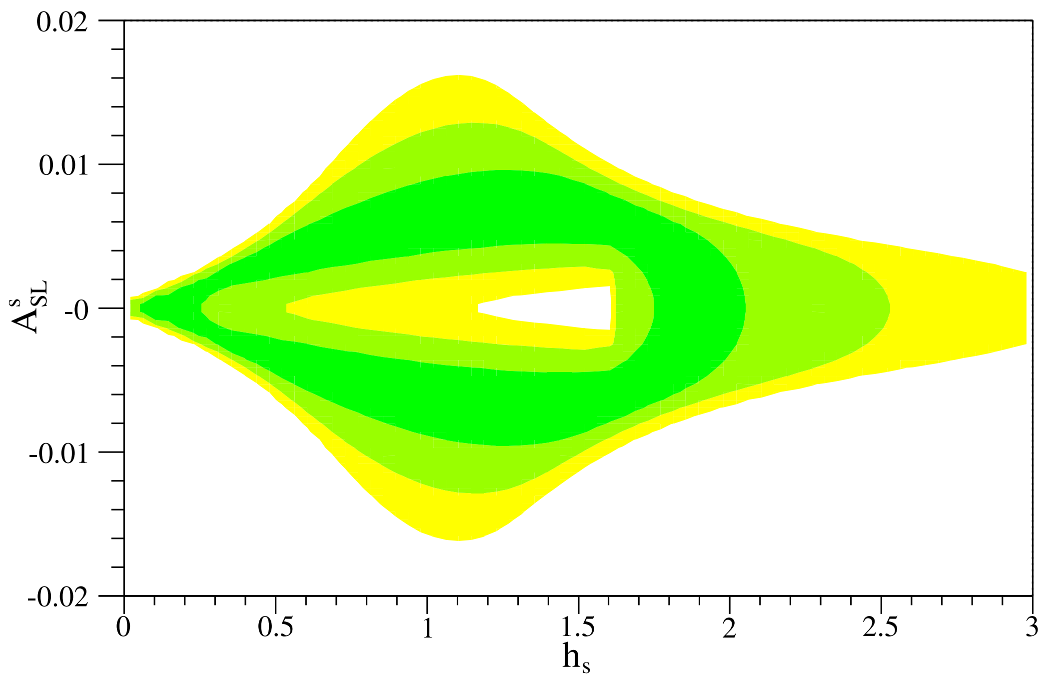
$$\gamma = (82 \pm 20)^\circ$$

- Both Babar and Belle use the frequentist method to quote the results — so shall I

CP violation in B_s mixing: $A_{\rm SL}^s$

- Difference of $B \to \overline{B}$ vs. $\overline{B} \to B$ transition probabilities

$$A_{\rm SL} = \frac{\Gamma[\overline{B}{}^0_{\rm phys}(t) \to \ell^+ X] - \Gamma[B^0_{\rm phys}(t) \to \ell^- X]}{\Gamma[\overline{B}{}^0_{\rm phys}(t) \to \ell^+ X] + \Gamma[B^0_{\rm phys}(t) \to \ell^- X]} = -2\left(\left|\frac{q}{p}\right| - 1\right)$$

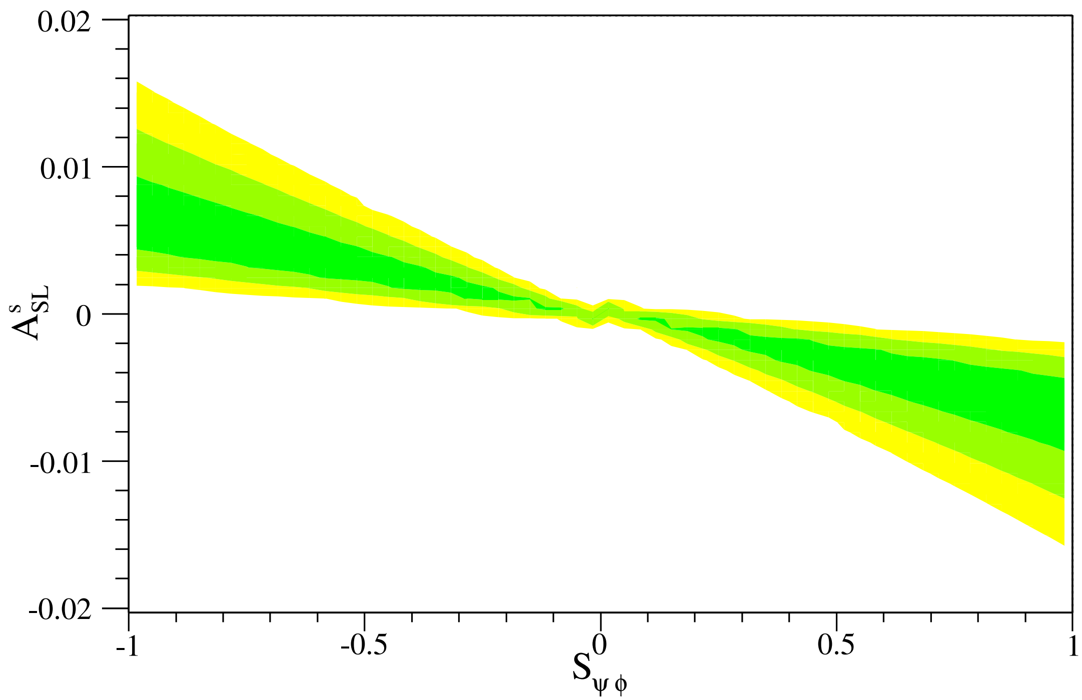


- Can be 3 orders of magnitude above SM; $|A_{\rm SL}^s| > |A_{\rm SL}^d|$ possible, contrary to SM

Correlation between $S_{\psi\phi}$ and $A^s_{\rm SL}$

- In $h_s, \sigma_s \gg \beta_s$ region $A^s_{\rm SL}$ and $S_{\psi\phi}$ are highly correlated

$$A^s_{\rm SL} = -\left|\frac{\Gamma^s_{12}}{M^s_{12}}\right|^{\rm SM} S_{\psi\phi} + \mathcal{O}\left(h_s^2, \frac{m_c^2}{m_b^2}\right)$$



- Deviation would indicate violation of 3×3 unitarity or NP at tree level

One-page introduction to SCET

- Effective theory for processes involving energetic hadrons, $E \gg \Lambda$

[Bauer, Fleming, Luke, Pirjol, Stewart, + ...]

Introduce distinct fields for relevant degrees of freedom, power counting in λ

modes	fields	$p = (+, -, \perp)$	p^2
collinear	$\xi_{n,p}$, $A^\mu_{n,q}$	$E(\lambda^2, 1, \lambda)$	$E^2\lambda^2$
soft	q_q, A^μ_s	$E(\lambda, \lambda, \lambda)$	$E^2\lambda^2$
usoft	q_{us}, A^μ_{us}	$E(\lambda^2, \lambda^2, \lambda^2)$	$E^2\lambda^4$

SCET$_\mathrm{I}$: $\lambda = \sqrt{\Lambda/E}$ — jets $(m{\sim}\Lambda E)$

SCET$_\mathrm{II}$: $\lambda = \Lambda/E$ — hadrons $(m{\sim}\Lambda)$

Match QCD $\to$ SCET$_\mathrm{I}$ $\to$ SCET$_\mathrm{II}$

- Can decouple ultrasoft gluons from collinear Lagrangian at leading order in λ

$$\xi_{n,p} = Y_n\, \xi^{(0)}_{n,p} \qquad A_{n,q} = Y_n\, A^{(0)}_{n,q}\, Y_n^\dagger \qquad Y_n = \mathrm{P}\exp\left[ig\int_{-\infty}^{x} \mathrm{d}s\, n\cdot A_{us}(ns)\right]$$

Nonperturbative usoft effects made explicit through factors of Y_n in operators

New symmetries: collinear / soft gauge invariance

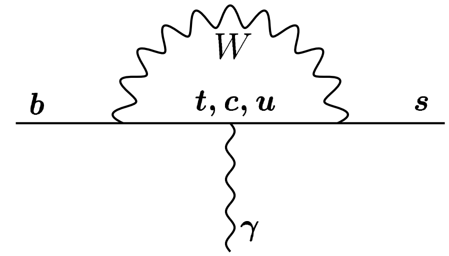
- Simplified / new $(B \to D\pi, \pi\ell\bar\nu)$ proofs of factorization theorems [Bauer, Pirjol, Stewart]

Photon polarization in $B \to X_s\gamma$

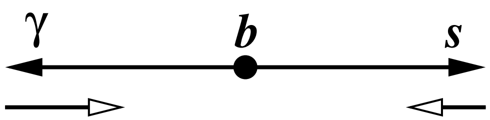
- Is $B \to X_s\gamma$ due to $O_7 \sim \bar{s}\,\sigma^{\mu\nu} F_{\mu\nu}(m_b P_R + m_s P_L) b$ or $\bar{s}\,\sigma^{\mu\nu} F_{\mu\nu}(m_b P_L + m_s P_R) b$?

  SM: In $m_s \to 0$ limit, γ must be left-handed to conserve J_z

  $O_7 \sim \bar{s}\,(m_b\, F^L_{\mu\nu} + m_s\, F^R_{\mu\nu})\, b$, therefore $b \to s_L \gamma_L$ dominates



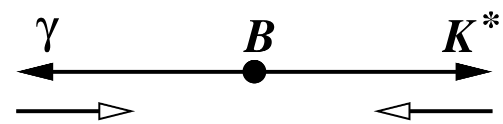
  Inclusive $B \to X_s\gamma$



  Assumption: 2-body decay

  Does not apply for $b \to s\gamma g$

  Exclusive $B \to K^*\gamma$



  ... quark model (s_L implies $J_z^{K^*} = -1$)

  ... higher K^* Fock states

- One measurement so far; had been expected to give $S_{K^*\gamma} = -2\,(m_s/m_b)\sin 2\beta$

  [Atwood, Gronau, Soni]

$$\frac{\Gamma[\overline{B}^0(t) \to K^*\gamma] - \Gamma[B^0(t) \to K^*\gamma]}{\Gamma[\overline{B}^0(t) \to K^*\gamma] + \Gamma[B^0(t) \to K^*\gamma]} = S_{K^*\gamma}\sin(\Delta m\, t) - C_{K^*\gamma}\cos(\Delta m\, t)$$

- What is the SM prediction? What limits the sensitivity to new physics?

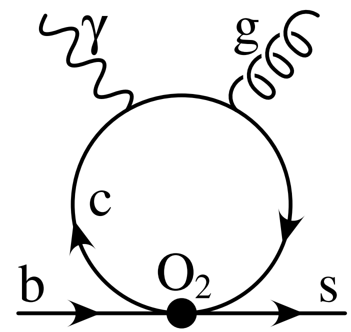
Right-handed photons in the SM

- Dominant source of "wrong-helicity" photons in the SM is O_2 [Grinstein, Grossman, ZL, Pirjol]

  Equal $b \to s\gamma_L,\ s\gamma_R$ rates at $\mathcal{O}(\alpha_s)$; calculated to $\mathcal{O}(\alpha_s^2\beta_0)$

  Inclusively only rates are calculable: $\Gamma_{22}^{(\mathrm{brem})}/\Gamma_0 \simeq 0.025$

  Suggests: $A(b \to s\gamma_R)/A(b \to s\gamma_L) \sim \sqrt{0.025/2} = 0.11$



- Exclusive $B \to K^*\gamma$: factorizable part contains an operator that could contribute at leading order in $\Lambda_{\mathrm{QCD}}/m_b$, but its $B \to K^*\gamma$ matrix element vanishes

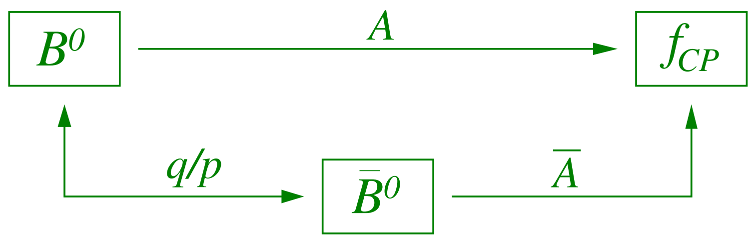
  Subleading order: several contributions to $\overline{B}^0 \to \overline{K}^{0*}\gamma_R$, no complete study yet

  We estimate: $$\frac{A(\overline{B}^0 \to \overline{K}^{0*}\gamma_R)}{A(\overline{B}^0 \to \overline{K}^{0*}\gamma_L)} = \mathcal{O}\left(\frac{C_2}{3C_7}\,\frac{\Lambda_{\mathrm{QCD}}}{m_b}\right) \sim 0.1$$

- Data: $S_{K^*\gamma} = -0.28 \pm 0.26$ — both the measurement and the theory can progress

CPV in interference between decay and mixing

- Can get theoretically clean information in some cases when B^0 and $\overline{B}^0$ decay to same final state



$$|B_{L,H}\rangle = p|B^0\rangle \pm q|\overline{B}^0\rangle \qquad \lambda_{f_{CP}} = \frac{q}{p}\,\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$$

Time dependent CP asymmetry:

$$a_{f_{CP}} = \frac{\Gamma[\overline{B}^0(t) \to f] - \Gamma[B^0(t) \to f]}{\Gamma[\overline{B}^0(t) \to f] + \Gamma[B^0(t) \to f]} = \underbrace{\frac{2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2}}_{S_f} \sin(\Delta m\, t) - \underbrace{\frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}}_{C_f\ (-A_f)} \cos(\Delta m\, t)$$

- If amplitudes with one weak phase dominate a decay, hadronic physics drops out

  Measure a phase in the Lagrangian theoretically cleanly:

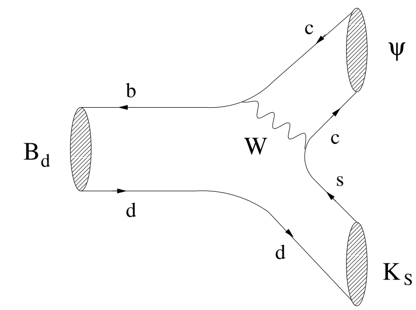
$$a_{f_{CP}} = \eta_{f_{CP}} \sin(\text{phase difference between decay paths}) \sin(\Delta m\, t)$$

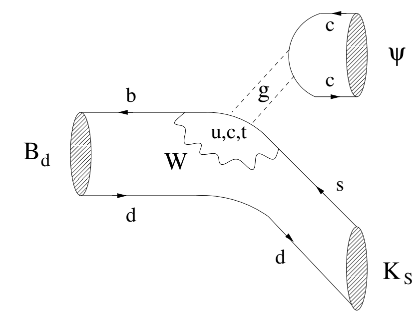
The cleanest case: $B \to J/\psi\, K_S$

- Interference of $\overline{B} \to \psi \overline{K}^0$ ($b \to c\bar{c}s$) with $\overline{B} \to B \to \psi K^0$ ($\bar{b} \to c\bar{c}\bar{s}$)

  Amplitudes with a second weak phase strongly suppressed
  (unitarity: $V_{tb}V_{ts}^* + V_{cb}V_{cs}^* + V_{ub}V_{us}^* = 0$)

$$\overline{A}_{\psi K_S} = \underbrace{V_{cb}V_{cs}^*}_{\mathcal{O}(\lambda^2)} \underbrace{\langle\text{“}T\text{”}\rangle}_{\text{“1”}} + \underbrace{V_{ub}V_{us}^*}_{\mathcal{O}(\lambda^4)} \underbrace{\langle\text{“}P\text{”}\rangle}_{\alpha_s(2m_c)}$$





  First term $\gg$ second term $\Rightarrow$ theoretically very clean

  $S_{\psi K_S} = -\sin[(B\text{-mix} = -2\beta) + (\text{decay} = 0) + (K\text{-mix} = 0)]$

  Corrections: $|\overline{A}/A| \neq 1$ (main uncertainty), $\epsilon_K \neq 0$, $\Delta\Gamma_B \neq 0$
  all are few $\times 10^{-3} \Rightarrow$ accuracy $< 1\%$

- World average: $\sin 2\beta = 0.675 \pm 0.026$ — a 4% measurement!

- Large deviations from CKM excluded (e.g., approximate CP in the sense that all CPV phases are small) $\Rightarrow$ Look for corrections, rather than alternatives to CKM